PHD

The flood resilience of light frame timber structures

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Award date:
2016

Awarding institution:
University of Bath

The flood resilience of light frame timber structures

submitted by

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for the degree of Doctor of Philosophy

of the

University of Bath

Department of Architecture and Civil Engineering

November 2015

Abstract

The UK faces a significant risk from flooding in the future, however the impact of flooding on structures is an area that has suffered from a lack of research. At the same time, more platform timber frame structures are constructed in the UK than ever before; a construction type that is susceptible to damage from flooding. This thesis explores the effect flooding and assisted drying have on the mechanical properties of current timber frame construction methods. A multi-scale, experimental approach is taken in order to characterise the response of timber frame to flooding, and to understand the effect that different assisted drying strategies have on the recovery of the mechanical properties of platform timber frame. The results provide new insight into the behaviour of platform timber frame during flooding and recovery. Permanent losses in all mechanical properties were observed at all scales tested. Despite the permanent losses, drying can be optimised to reduce the reduction in strength and stiffness of walls. In the wall tests, buckling failure of the OSB sheathing was observed after restoration via assisted drying. This is a change in failure mode to one that has not been observed before and one that is not accounted for during design. This buckling failure is used to partially explain the loss in capacity observed. Finally the experimental results are used to develop a proposed design method for the repair of platform timber frame after flooding.

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Acknowledgments

Firstly I would like to thank my supervisors Wen-Shao Chang and Richard Harris for their support throughout this project. They gave me the freedom to explore ideas and gently guided me towards the successful ones. They have been invaluable and without them I would still be writing.

The entire departmental laboratory team also deserves huge thanks. Their efforts and advice enabled me to perform the experiments that were so critical to my project. Special mention must also go to the following; Glen Stewart and Walter Guy for their patience in teaching me the basics of carpentry and in preparing my numerous samples, Will Bazely for his insight and advice, especially designing experimental set-ups and also Eve Walkden for her tireless efforts and support at the HIVE facility. Finally I must thank Ewan Basterfield without whom there would have been no drying equipment and no experiments.

During the course of my PhD I have been lucky enough to have met a fantastic group of people. Friends from both inside and out of the University who challenged and influenced me. They made my time in Bath complete and about more than just the PhD research. A special thanks to Nick Williams, Manuel Nuño, Dragos Naicu, Alex Reilly, Josh Graham and Dom Van Der Waals.

To my parents; your constant love and support, not just during my PhD but throughout my life has ensured that I am where I am today. Thank you for instilling a love of learning and discovery in me. I could not have achieved what I have without you. I am so grateful for all you have done, and all you continue to do for me.

Finally, Jane. What serendipity meeting you and what joy you have brought me. I love you.

Twickenham
November 2015

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Chapter 1

Introduction

1.1 Background

Flooding affects more people globally than any other natural disaster [1]. For the UK, it is one of the most significant risks to the country in the coming century. In England it is currently estimated that over 5 million, or 1 in every 6, properties is at risk of flooding [2]. The UK has experienced significant flooding in the last decade. The summer of 2007 saw some 55,000 properties flooded. The total damage bill for the entire clearup exceeded £3 billion [3]. Flooding in 2012 was directly responsible for claiming the lives of nine people, as well as causing billions of pounds worth of damage to property. The winter of 2013/14 saw much of Somerset flooded for many months; in places, the flood waters were reported to be up to 4 m deep [4]. The financial impact of flooding is significant and the annual cost of recovery has been estimated to be in the region of £1.1bn per year [2].

As a result of anthropogenic climate change, flooding is set to become more likely [5]. With more periods of intense rainfall predicted, the likelihood of flood events is increased. This increase in flood risk comes at a time when spending on flood defences is being cut. Total funding decreased 10% in cash terms between 2010/11 and 2014/15 [6].

In conjunction with increased risk of flooding, the UK also faces a shortage of housing. Fewer houses were built in 2010 than in any year since the Second World War. House construction in the last decade has annually, only matched half of that required to meet demand. Just 120,000 of the 240,000 homes required each year are built. This *chronic under-supply of housing...*" [7] has led to a so called "*housing crisis*" [8].

Simply put, in order to address this crisis, more homes must be constructed. One way in which this can be achieved is through the use of timber frame. Timber frame has a low carbon footprint and is ideally suited to off-site manufacturing production, utilising lean manufacturing techniques [9]. The high quality control and low degree of wastage achievable make it a cost effective method of construction. Compared to other construction types, the speed of on-site assembly is greatly increased through the use of pre-fabricated sections. Due to its construction speed and low cost, timber frame is an ideal method to exploit in order to address the current UK housing shortage. The speed of construction and environmental credentials of timber frame make it particularly suited to modern building, and it is for these reasons that timber frame is in a period of rapid growth. Despite a downturn in the housing construction industry following the 2008 financial crisis, timber frame construction has continued to grow [10].

Currently, approximately 23% of all new build "*dwelling types*" is timber frame [10]. Despite the inherent risks associated, this new housing is likely to be constructed in sites of high flood risk or on flood plains [3, 11]. As such, it is wise to invest in appropriate, economic methods with which to protect housing stock from flooding.

Currently however, research into the performance of buildings and their components during floods is severely lacking. No research exists that adequately investigates the effect flooding has on the structural performance of timber frame. Furthermore, no research has been carried out into optimum methods of drying timber frame. As a result, the available guidance is contradictory and has unaddressed gaps. This has led to variations in the approaches used to dry and restore structures after flood. It can take many months to recover from flood and it is not uncommon for repeat drying and repair to be required because it was performed incorrectly in the first instance.

The motivation for this thesis is therefore to address the gaps in existing knowledge and determine how timber frame performs during and after flooding. Given the increase in the use of timber frame and the risk the UK faces from flooding, this is an important area of research. In this thesis, an experimental approach is taken in order to develop an understanding of the performance of timber frame when exposed to flooding. Efficacy of drying method is studied as a function of the recovered mechanical properties following flood. These values are compared for different drying environments in order to determine optimum drying conditions for timber frame. By comparing performances of timber frame before and after flooding, new insights into its change in behaviour due to wetting and drying are developed. As a result of the experimental data, new understanding about reductions in structural performance is available. Ultimately, it is hoped that this research will provide a platform for designing better repair processes as well as improving construction choices in terms of material and detailing.

1.2 Focus of thesis

This thesis is a study into the flood resilience of light weight, platform timber frame structures. Clearly, this is a broad topic with many research avenues. Macro-scale approaches, such as investigating the impact of existing legislation or modelling how urbanization and changes in land use affect flood risk in an area are not considered as they are outside of scope.

The Department for Communities and Local Government in its publication "*Improving the Flood Performance of New Buildings*" [12], suggests there are four main strategies to limiting flooding that can be adopted on the micro-scale. Here micro-scale refers to an individual structure or group of structures. These strategies are:

1. Flood avoidance at a site level
    - Constructing a building and its surroundings to avoid flooding, for example; build away from flood risk or raise above flood level.
2. Flood resistance

- Construct a building such that flood water is prevented from entering and causing damage.
- This could include flood barriers fitted after construction.

3. Flood resilience
    - If water enters a structure, it is designed such that no permanent damage occurs.
    - Structural integrity is maintained and drying and cleaning are facilitated.
4. Flood repairable
    - Elements of a building that are water damaged are easily replaced or repairable.
    - This is arguably a subset of flood resilient construction.

From the above list, this thesis will focus on items 3 and 4, the resilience and repair of timber structures. In order to develop an understanding of the current flood performance of timber frame, avoidance of flood and prevention of water ingress are not investigated.

1.3 Thesis organisation

Chapter 2 presents a review of relevant background literature to the project. Multiple topics must be understood in order to provide background and context to the research. The impact of flooding, flood recovery guidance and the current UK housing market are all explored. In addition, definitions of specific terms used throughout the thesis, such as "timber frame", are given. The chapter concludes with a summary of the important findings. These findings inform the direction of the rest of the research project.

In Chapter 3, the methodology is given and the project aims are stated. General experimental approaches common to all sections of the thesis are discussed. This chapter is informed by the information discussed in Chapter 2.

Chapter 4 presents results of tests conducted on single nailed connection specimens, designed to model the sheathing to timber connections in typical timber frame construction. The connection specimens are used to investigate the reduction in mechanical properties and to explore different drying environments for efficacy. Parts of this chapter were presented as a peer reviewed paper in the *Construction Materials* journal, published by the Institution of Civil Engineers, see [13].

In Chapter 5, the effect of flooding on full shear wall assemblies is studied. This chapter builds on the work presented in Chapter 4 by extending the study focus from a single critical component of the structure to the whole structural system. Mechanical properties and failure modes of the shear walls are reported. These results have been accepted for publication in the Elsevier journal, *Engineering Structures*.

Chapter 7 summarises the experimental data presented in the previous two chapters. The importance of the results regarding the response of timber frame to flooding and their implications for repair of timber frame are discussed. A process for calculating the design strength after flood is proposed. The limitations of the research are also discussed and possible future work is presented. Chapter 8 presents the overall conclusions of the thesis. Finally, Appendix A provides details on the Taguchi method that is used in Chapter 4.

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Chapter 2

Literature Review

2.1 Introduction

As briefly outlined in Chapter 1, flooding causes severe damage and is a major risk to property in the UK. It was also stated in Chapter 1 that this thesis would investigate only the resilience and repair of timber structures. To effectively research the effect flooding has on these aspects of timber frame construction requires an understanding of a number of different but interdependent areas. This chapter explores these areas and provides the context and background for the research project. The findings of this chapter inform and influence the experimental decisions taken later in the project. The areas that must be understood are as follows:

- To what extent is the UK at risk from flooding?
- What is is meant by timber frame?
  - What materials are used in its construction?
  - What specific details apply to timber frame construction and use in the UK?
- How is the strength of timber frame construction modelled for design?
- What is the relationship between timber properties and moisture content?

- What the influence of moisture content on the mechanical properties of timber and timber based products?
- How is moisture content in timber measured?
- What are the likely effects of increasing moisture content due to flooding of timber frame?
- What are the effects of drying on the mechanical properties of timber and timber based materials?

- What existing guidance is there on the repair and restoration of timber frame after flooding?
  - What research exists to inform this guidance?

The above areas will be explored in detail, each in their own section. The chapter concludes with a final discussion and summary that combines all of the threads into the background for the project. As will be seen in the following sections, the effects of flooding on structures are a much under researched area, especially where timber frame is concerned.

2.2 Flooding

Flood is defined by the Oxford English Dictionary as:

> **flood**,*n.*
> 4. a. *An overflowing or irruption of a great body of water over land not usually submerged; an inundation, a deluge. in flood, †on (a) flood : (of a river, etc.) overflowing its banks; (of land) in an inundated condition.*
> 5.a. *A profuse and violent outpouring of water; a swollen stream, a torrent; a violent downpour of rain, threatening an inundation.*[14]

As discussed in Chapter 1, globally flooding affects more people than any other natural disaster [1]. The number of people affected world wide by flood has risen significantly since 1940, see Figure 2-1. Flooding can occur from a number of sources, both natural (river and coastal flooding, surface water flooding) and man-made (sewer flooding and from sources such as burst internal pipes). Regardless of the source, flooding can quickly cause significant damage. Factors such as flood depth, duration, water velocity and debris carried in the flood water are important in determining the impact of a particular flood event [15]. Lateral pressure caused by a difference in water depth on faces of a wall is also noted as highly damaging [15, 16].

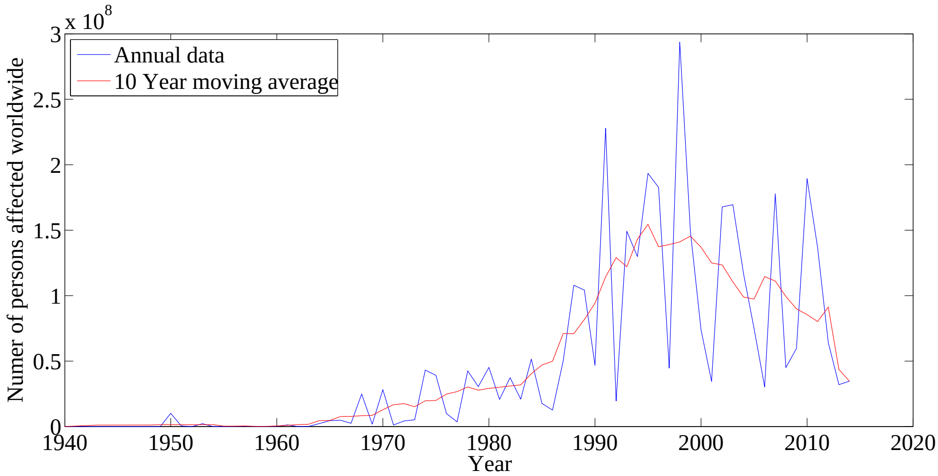


Figure 2-1: Numbers of people affected world wide by flooding annually. The annual data are compared with the 10 year moving average. Data from [17].

The Environment Agency (EA) defines three classes of flood risk; low, medium and significant [18], the definitions of which are given in Table 2.1. In North Somerset, approximately half of all properties are at "significant risk" of flooding and in London, over one million people live on the flood plain [18]. Of these 542,000 properties, 84% are at low risk of flooding. The remaining 16% of properties are split approximately evenly between the medium and significant risk categories [18]. The manifestation of these risks in the UK is significant, for example, the winter of 2013/14 saw much of the Somerset levels completely submerged for many months and those affected displaced from their homes for up to 18 months.

As a result of anthropogenic climate change, weather that leads to flooding is set to become more likely [5]. Statistical models produced by the University of Oxfords' "*weather@home*" project suggest that the risk of a very wet winter in

Table 2.1: Flood risk categories as defined by the Environment Agency [18].

Category	Annual percentage chance of flooding	Return period
Low	< 0.5 %	$<$ 1 in 200
Medium	0.5 - 1.3 %	1 in 200 - 1 in 75
Significant	> 1.3 %	$>$ 1 in 75

the South of England has increased by 25% [19, 20]. With more periods of intense rain predicted, the likelihood of flood events is increased.

An excellent example of the severity of the threat faced by the UK are the 2007 summer floods. These floods were so severe they were later described by Sir Michael Pitt as "*... the country's largest peacetime emergency since World War 2*" [3]. The floods in 2007 damaged some 55,000 properties, trapped 10,000 people on motorways, left 350,000 people without mains water for more than two weeks and the recovery cost in excess of £3 billion [3]. The severity of the events was a great driver for change and as a result, the Pitt Review [3] was commissioned in order to understand what lessons could be learned. The recommendations of the Pitt Review were almost entirely adopted by the government [21] and resulted in new legislation; the "Flood and Water Management Act 2010". The act enables a more complete management of flood risk by setting out who is responsible for managing flood risk, placing the environment agency in a strategic overview role and tasking local authorities with managing local flood risk. It provides a single framework which allows for, and requires, cooperation between different responsible agencies. More recently, schemes such as "Flood Re" [22] have been introduced. Flood Re is legislation intended to provide affordable insurance to those whose properties are at a high risk of flooding [23] by placing a levy on on other insurance policies. The cost effectiveness of the schemes has been questioned by some for being too expensive or poor value for money [24–26].

Despite knowing the risk and potential impact of flooding to the UK, flood defence spending is being cut. During the 2010/11 to 2014/15 parliament, planned total funding for flood protection measures decreased, in cash terms, by 10% [6]. Flood risk management is arguably however, a more nuanced problem than just simple cash spending on defence measures. There has been a move away from simplistic flood defence measures to a more holistic approach to flood management [27].

Schemes such as those in Lancashire where salt marshes are used to limit the effects of coastal flooding are good examples of this policy [28]. This approach is arguably cheaper with better long term cost benefits than traditional flood defence schemes. In addition, the maintenance of existing infrastructure is less expensive than the construction of new, therefore requiring a smaller budget.

In the next spending review period, even with planned budget cuts, by 2021 the Department for Environment, Food and Rural Affairs (Defra) aims to have reduced flood risk by 5% by better protecting 300,000 households [29]. This will be achieved, in part, by attracting up to £600 million in additional partnership funding from the private sector [29]. However, much of this reduction in risk will be achieved by moving properties at medium risk of flooding to the low risk of flooding category and in fact, the total number of properties at high risk may actually increase [24].

As Defra note in [29], the risk of flooding can never be eliminated. The long term consequences of budget cuts on flood risk remains to be seen. The effectiveness of plans by Defra to reduce flood risk by 5% are also subject to political shifts. Reliance on attracting private investment in the future [29] and differences in political opinion over budget cuts make the current funding system particularity susceptible to changes in the political landscape.

Studying the impact of introductions and changes to flood management legislation is not the purpose of this thesis. The examples here only serve to illustrate how complex an issue the management and governance of flood risk is. What is clear is that flood will continue to be a risk for property owners of all types. Despite insurance guarantees and efforts to better protect at risk structures, flooding will still happen and homes and businesses will continue to suffer damages. When flooding occurs, the process of cleaning up and returning to normal is of paramount importance.

2.3 Timber Frame

Timber frame can refer to many construction styles. In this thesis, only one type of timber construction is considered, light weight platform timber frame. More detail is given in Section 2.3.1.

Chapter 1 introduced the current housing shortage that the UK faces. One way in which the housing shortage can be addressed is through the increased use of timber frame. Timber frame has a low carbon footprint and is well suited to exploit off-site production and lean manufacturing techniques [9]. Many UK house builders such as Stewart Milne [30] and Persimmon [31] now produce large volumes of pre-fabricated timber housing.

The Cabinet Office Construction Strategy [32] places emphasis on efficiency, low waste and value for money during construction projects. Within this policy framework, timber frame is ideally suited for use in publicly funded projects such as schools or hospitals as well as privately funded house construction projects. The speed of fabrication and erection [33], combined with its environmental credentials means timber frame is becoming more widely adopted. In the year 2000, timber frame accounted for just 12% of the UK new build housing market. By 2012 this figure had grown to approximately 23% [10].

Due to a slow down in the house building market as a result of the 2008 global recession, market share growth of timber frame to around 30% of new build [34] by 2015 has not been as predicted. Instead, the market share of timber frame is expected to hold steady or experience a slight growth in the next few years [10]. Despite these challenging conditions which have affected all construction types, timber frame has continued to be adopted more widely. The total market share of new build timber frame construction rose to 76% in Scotland and 16% in England [10]. Its use was particularly notable in the social housing sector. In Scotland 86% of publicly funded, new build social housing was constructed using timber frame and in England the figure was 36% [10]. In contrast, timber frame accounted for just 11% of the English private market [10]. Despite difficult times for all construction, timber frame has continued to remain a popular choice, even during a construction downturn. As construction picks up, the low cost, environmentally friendly credentials and speed of construction of timber frame will continue to make it an attractive prospect.

2.3.1 What is Timber Frame?

At the beginning of Section 2.3 it was stated that only Platform timber frame would be studied. Within the context of this thesis timber frame (TF) will be taken to mean a light weight framing system comprising timber members arranged in a rectangular frame, with a sheathing board nailed to one or both sides to provide lateral stiffness. Horizontal bottom and top rails are connected to evenly centred vertical studs via a nailed connection. The sheathing board is fixed to the framing and provides horizontal shear resistance to the structure. The in-plane lateral resistance of a wall is referred to as the racking resistance or racking strength [35]. The sheathing used is most commonly Oriented Strand Board (OSB) or Plywood. This style of construction is the most prevalent construction methodology in North America, accounting for some 90% of domestic construction [36].

There are two main types of framing, balloon framing and platform framing. In the UK the most common form of light timber framing is Platform Timber Framing [35, 37], accounting for approximately 23% of the total UK new build housing market [10]. Platform timber frame (PTF) comprises two basic elements; shear walls and diaphragms. Both are structural elements designed to transmit forces in-plane [38]. The term *shear wall* refers to the upright walls of the structure whereas *diaphragm* refers to the structures' horizontal floor sections. Walls are constructed from multiple shear wall sections joined together to form the required length. Racking resistance of a wall is the sum of the resistance of its individual sections.

A floor diaphragm is supported by the shear walls underneath and, in turn, provides support for the walls of the storey above. Figure 2-2 on page 30 illustrates a typical wall panel construction.

Balloon framing is less common in the UK. The balloon frame has the same structural components as PTF however, instead of each storey supporting the next, the floors are hung off full height walls. Balloon framing is not considered in this thesis.

The void in the wall formed by the studs and sheathing is filled with insulation materials. Insulation requirements often dictate wall thickness and therefore stud

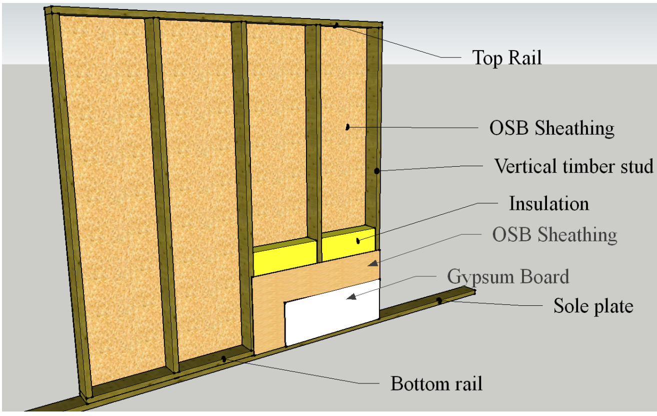


Figure 2-2: Cut away illustration of a typical timber frame wall panel. Framing, with vertical studs on 600 mm centres and OSB sheathing is shown. Walls are anchored to a sole plate which is fixed to the foundations of the structure. Insulation is used to fill the void between studs and sheathing. Insulation requirements often dictate stud size [39].

size, see Section 2.3.2. Walls can be sheathed on one or both sides and the inner face of the wall normally has gypsum plaster board or similar fixed to it [35, 39]. According to Patton-Mallory et al. [40], the increase in strength as a result of more than one sheathing layer is additive, although this behaviour is modified by design codes to be more conservative [41], see Section 2.4.2. The sheathing in the wall is normally fastened to the timber frame by means of a simple nailed connection. The connections between the timber frame and the sheathing are often critical in governing wall strength [42]. Studies have shown that connection strength can be used to successfully predict shear wall strength [43–49]. This relationship is logical as the sheathing provides the lateral resistance of the wall. Forces applied to the wall must be transferred from the timber frame into the sheathing and this is achieved via the nailed connection between the sheathing and framing, hence the relationship between wall strength and sheathing to timber connection.

Walls are fixed to the structural foundation via a *sole plate*. This sole plate is a timber member fixed to the foundations to which the bottom rail of a wall is then anchored, see Figure 2-2. The sole plate acts as a junction that allows easy fixing between the timber frame and the foundation material, typically concrete. More details on the anchoring of walls are given in Section 2.3.3.

2.3.2 Timber frame construction details

Platform timber frame is defined by the Institution of Structural Engineers (IStructE) as:

> "*…a structural sheathing material (usually OSB/3) and plasterboard nailed or screwed onto opposite sides of softwood framing and studwork with the spaces filled by a suitable insulating material*" [39].

The IStructE [39] expands on this definition, stating:

> "A typical construction for walls without openings in buildings up to four storeys is:
>
> - structurally graded C16 framing members, specified with "no-wane" cross-section 38 mm × 89 mm, 44 × 97 mm or 38 × 140 mm (depth governed by thermal insulation requirements and method of insulation - 140 mm is increasingly common)
> - stud spacing 600 mm (maximum); where possible spacing should match joist centres which are normally 600 mm but may be 400 mm or 450 mm to reduce depth.
> - top and bottom rails nailed to studs with a minimum of 2 no. nails of 3.0 mm Φ galvanized smooth round steel wire nails or 3.1 mm Φ machine-driven galvanized steel nails, 75 mm long.
> - external sheathing 9.0 mm thick OSB/3
>   - for class 2 buildings fastened to studs with 3.35 mm Φ galvanized smooth round wire nails or 3.1 mm Φ galvanized machine-driven steel nails; all at least 50 mm long, spaced at 150 mm on perimeter, 300 mm on internal studs."

The above definition gives specific details of numbers of nail, nail type and length. In practice, a single nail type is generally used throughout. This is normally a 3.1 mm Φ, machine driven galvanized steel nail, 90 mm in length [39].

2.3.3 Foundation fixing

The method in which shear walls are fixed to the sole plate in a structure has great influence on their behaviour during loading. Horizontal sliding forces, shear forces and overturning forces in the wall must all be resisted. This resistance can be provided in a number of different ways such as hold down brackets or a nailed or bolted connection between the bottom rail and sole plate [9, 35, 38]. Horizontal resistance is provided by connections between the bottom rail and sole plate. These connections transfer the forces into the foundations via the sole plate [35]. On site, the sole plate can be fixed in a number of ways, some examples of which are detailed in [9]. Vertical resistance can be provided from a number of sources such as:

- end tie downs fixed directly to the vertical end studs
- transverse walls
- vertical loads from upper storeys
- contribution by the anchors used to resist horizontal forces
- a combination of all of the above.

Further details can be found in [35, 38] and [50].

If a wall is anchored using tie downs attached directly to the end studs it is referred to as a fully anchored wall, as illustrated by Figure 2-3. In a fully anchored wall, uplift is resisted by the tying down device. This results in a concentrated force at the end of the wall in the leading stud. There is no uplift of the leading stud in a fully anchored wall [50].

In contrast, a partially anchored wall does not have tie downs on the end studs [50]. In partially anchored walls, horizontal and vertical resistance is provided by the connection between the bottom rail and sole plate. The partially anchored wall has some uplift of the leading stud when loaded. This is illustrated by Figure 2-4. The two different anchorage approaches result in different wall behaviour, see [50].

In the UK, it is rare to use tie downs in domestic construction [35]. The majority of UK timber frame structures are therefore partially anchored. In a partially

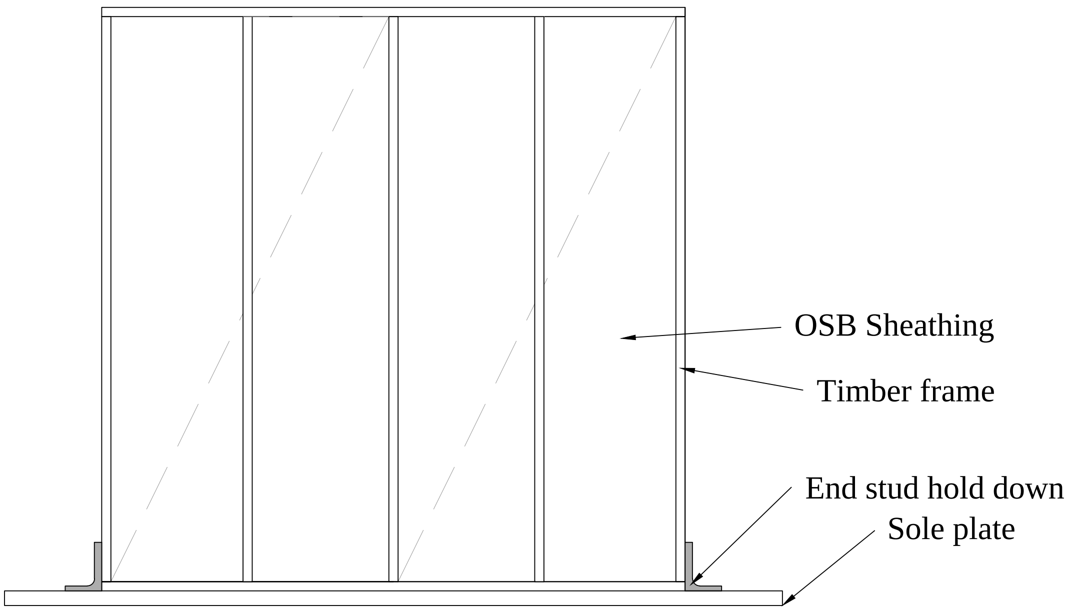


Figure 2-3: Illustration of a fully anchored wall. End studs are directly anchored using hold down ties. No other fixings are used.

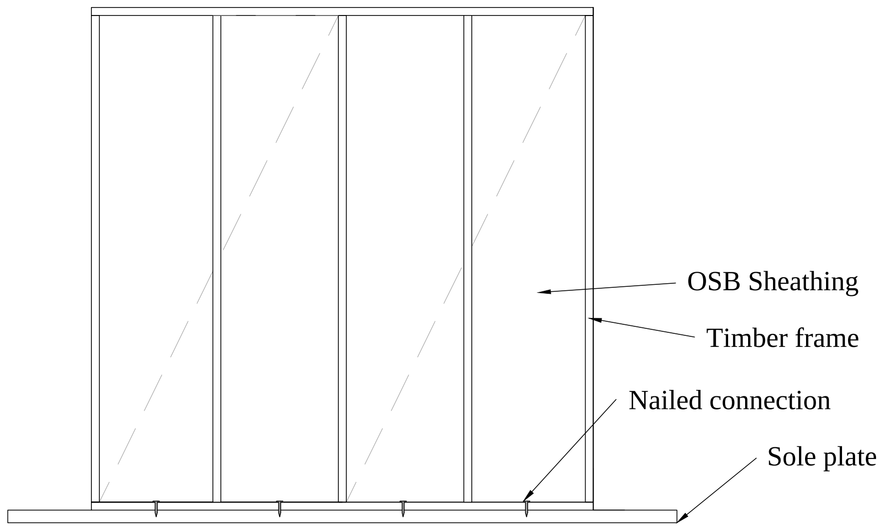


Figure 2-4: Illustration of a partially anchored wall. Bottom rail is anchored using a nailed connection between each stud. Unlike in Figure 2-3, the end studs are not directly anchored.

anchored wall the sheathing-to-framing joints along the bottom rail counteract the uplift forces the wall is subject to. The applied loads are transferred from the nails connecting the sheathing to framing into the bottom rail. The forces are then transferred from the bottom rail to the sole plate via the connection between the two. Forces are finally transferred to foundation via the sole plate anchors. In this case, the connection between the bottom and sole plate is subject to both shear forces and tensile forces [50]. Because the bottom rail-sole plate connection and sheathing-to-framing joints must resist both shear and uplift, the racking capacity of the wall is reduced [50]. According to Girhammar et al. [50], "*...Essentially no recommendations are given in the present European codes*" regarding anchor design. Various design documents do however give recommendations. Porteous and Kermani [35] note that generally, "*horizontal sliding is resisted by anchorages such as nails or bolts...*". More specific guidance is given by Porteous and Ross [51], stating that "*...the default fix through the bottom rail provided by framers is usually nails at 300 mm centres...*". Furthermore, according to the IStructE [39] anchoring can be achieved by a single nail of 4 mm Φ with a point side penetration of at least 37 mm, driven between each vertical stud. This will provide adequate resistance for uplift and sliding when acting in conjunction with the structure self weight and the contribution of return walls. Without the action of vertical loads on a structure such as the weight of upper storeys, nails provide low withdrawal resistance between the bottom rail and sole plate. Where bolts are specified they are used in conjunction with large diameter washers and tightened until the washer bears into the timber. Bolts provide greater withdrawal resistance although their use can result in failure of the bottom rail due to either splitting or cupping, [50, 52].

2.3.4 Summary

In this thesis, timber frame has a specific definition. It refers to a light weight framing system comprising solid timber studs and rails assembled into a rectangular frame, with sheathing board fixed to the stud work. Typically, in the UK the sheathing used is OSB and a single nail type is used throughout. This is normally a 90 mm long, 3.1 mm Φ, galvanised steel nail. The frame can be fixed to the foundation such that it is termed either fully or partially anchored. Fully anchored structures are rare in the UK. The majority of platform timber frame in the UK is partially anchored.

2.4 Sheathing to timber connection properties

As mentioned briefly in Section 2.3.1, the connection strength between the sheathing and timber is directly related to the strength of the shear wall. Shear walls derive their resistance to loading from the shear resistance provided by the sheathing board. The timber frame itself, without any sheathing fixed to it, acts as a mechanism when laterally loaded. Since the structural system is reliant on the sheathing resistance to withstand loading, clearly the connection between the sheathing and the frame is critical. This relationship has long been recognised [49]. Although Dolan and Madsen [43] note that many connection characteristics translate "*directly...*" into nailed timber shear wall behaviours it is worth noting that the stiffness of the connection does not translate so well. A study by Okabe et al. [44] found that connection strength is closely correlated to wall strength but stiffness does not. The reason for this is simple, a single nailed connection connection has limited scope for generating stiffness. A shear wall is more complex with more capacity for generating stiffness.

The relationship between connection behaviour and wall behaviour forms the basis of the current European and British design codes. Källsner and Girhammar have produced a series of papers on the problem of predicting the ultimate strength of timber shear walls. Their work forms the basis of PD 6693-1 [41], the current code for timber shear wall design in the UK, as well as the basis of "Method B" given in Eurocode 5 [53]. Both Eurocode 5, Method B and PD 6693-1 are based on a model in which moments are taken about the wall and the plastic lower bound method or, static theorem [54], is used to determine the ultimate strength of a shear wall.

2.4.1 Connection strength and wall strength relationship

In their 2004 CIB/W18 paper, "*Influence of framing joints on plastic capacity of partially anchored wood-framed shear walls*" [46], Källsner and Girhammar give proposed force distributions for partially anchored shear walls at their plastic limit when subject to external loading. The solutions to the moment equilibrium equations give a lower limit for the ultimate racking strength of a wall. In their model, the ultimate strength of the nailed connections, expressed as a per unit length value, is used to determine the capacity of the wall when solving the moment equilibrium equations.

Källsner and Girhammar give a number of versions of their model in [46], each increasing in complexity. The final model presented forms the basis of the design code approaches and includes the influence of the framing joints on the capacity of the wall. Their model is expanded in Källsner and Girhammar [48] to account for wall openings and Källsner and Girhammar [55] to account for multi story buildings. Comparison of experimental results presented by Girhammar and Källsner [47] and calculated results shows good agreement. The accuracy of their approach using connection strength to predict wall strength highlights the close relationship between the connection strengths and wall strength.

2.4.2 Application to design codes

The model presented by Källsner and Girhammar [46] forms the theoretical basis of Eurocode 5, Method B [53] and of PD 6693-1 [41]. The design model approach is covered in great detail by Porteous and Kermani [35]. Although the codified approach is based on Källsner and Girhammar [46], it is not identical. For example, the withdrawal strength of the fasteners anchoring the bottom rail to the sole plate are used as the limiting factor for wall strength in the design code whereas Källsner and Girhammar limit the wall strength according to the sheathing to timber connection strength.

In PD 6693-1, the horizontal racking strength of a wall diaphragm, $F_{i,v,Rd}$, is given by Equation 2.1:

$$F_{i,v,Rd} = K_{opening}\, K_{i,w}\, f_{p,d,t}\, L \tag{2.1}$$

where:

- L is the wall length in meters.
- $f_{p,d,t}$ is the summation of the design shear capacities of the perimeter sheathing fasteners in kN/m.
- $K_{i,w}$ is a modification factor accounting for wall length, vertical loads and hold down arrangements.
- $K_{opening}$ is a modification factor accounting for the effect of openings.

Values of $K_{opening}$ are given in PD 6693-1, specifically Sections 21.5.2.7 - 21.5.2.8. The sheathing to timber connection capacity, $f_{p,\,d,\,t}$, is a summation of the capacities of all sheathing to timber connections in the wall. This allows the contribution of sheathing on both sides of the diaphragm or double layered sheathing to be included.

$$f_{p,d,t} = f_{p,d,1} + K_{comb}\, f_{p,d,2} \tag{2.2}$$

In Eqn. 2.2, $f_{p,d,2} \leq f_{p,d,1}$ and the value of K_{comb} must be between 0 and 0.75. Values of K_{comb} are given in Table 8 of PD 6693-1 and vary depending on the sheathing configuration. The additive nature of the strength gain from additional sheathing layers is therefore modified by the design code via the K_{comb} factor to be conservative.

The parameter $K_{i,w}$ is given by Eqn. 2.3:

$$K_{i,w} = \left[1 + \left(\frac{H}{\mu\, L}\right)^2 + \left(\frac{2M_{d,stb,n}}{\mu\, f_{p,d,t} L^2}\right)\right]^{0.5} - \left(\frac{H}{\mu\, L}\right) \tag{2.3}$$

where:

$$\mu = \min \begin{cases} 1 \\ \frac{f_{w,d}}{f_{p,d,t}} \end{cases} \tag{2.4}$$

and H = height of wall. In Eqn. 2.4, $f_{w,d}$ is the design withdrawal strength of the bottom rail to floor connections per unit length (kN/m). Through the use of the parameter μ, Equation 2.4 limits the strength of the wall as a function of the withdrawal capacity of the bottom rail to floor connections. PD 6693-1 states that $f_{w,d} \leq f_{p,d,t}$. If $f_{w,d} > f_{p,d,t}$ then the sheathing connection strength becomes the failure condition [35].

The net stabilising moment in Eqn. 2.3, $M_{d,stb,n}$, is found by subtracting the destabilising moment produced by wind loading from the stabilising moment of the vertical loads.

Finally, $f_{p,d}$ is determined according to Eqn. 2.5:

$$f_{p,d} = \frac{F_{f,Rd}\,[1.15 + s]}{s} \tag{2.5}$$

where s is the sheathing fixing spacing in meters and $F_{f,\,Rd}$ is the design lateral capacity of a lateral fastener in kN. The increase in fastener capacity, $[1.15 + s]$, is similar to the modification factor of 1.2 which is commonly used to convert characteristic strength values to mean strength values. According to Porteous and Kermani [35], the Eurocode 5 argument is that "*...where a significant number of fasteners are loaded in a line configuration, the probability that all fasteners will only achieve the characteristic strength value is beyond the design basis and the code allows the mean strength value to be used*". This factor enables the characteristic strength of a connection to be converted to the mean strength. In PD 6693-1, using a nail spacing of 50 mm gives the modification factor for nail strength as 1.2. At the maximum nail spacing of 150 mm, the modification factor is 1.3. Equation 2.5 therefore makes the mean sheathing connection capacity a function of the fastener spacing.

Although based on the model developed by Källsner and Girhammar [46], the exact procedure and approach laid out in PD6693-1 [41] model differs. The approach by Källsner and Girhammar [46] makes the sheathing to timber connection capacity the limit of wall strength. In contrast, the PD 6693-1 approach uses the withdrawal capacity of the bottom rail to foundation fasteners to limit the design strength, Eqn. 2.4. The horizontal shear capacity of framing joints are used by Källsner and Girhammar [46] to increase the strength whereas in PD 6693-1 it is not clear whether this effect is accounted for. The approach taken in design codes is of course necessarily simpler and more conservative compared to the underlying theory it is based on.

In this thesis, the aforementioned models will be used to compare experimental results. More detail on the specific use of the models with experimental data is given in Chapters 4 and 5 where appropriate.

2.5 Moisture content of timber

When flooded, timber and timber based products will absorb water. The moisture content of timber is an important property that in part governs its mechanical properties and durability. As moisture content decreases, the strength of timber increases [56]. Moisture content (MC) is defined as the percentage by mass, of water present in timber [57, 58].

$$MC(\%) = \frac{m_1 - m_0}{m_0} \times 100 \tag{2.6}$$

In Equation 2.6, m_1 is the mass of timber before drying and m_0 is the oven dried mass of the timber. The oven dried mass is determined by drying timber samples at 103 $^0C \pm 2$ ^{0}C until the difference in mass between two successive weighings, separated by two hours, is less than 0.1% [57]. The wet and dry weights are then used to calculate the moisture content by mass. This gravimetric method is a direct measure of the moisture content of a timber specimen however, it is slow and can be impractical depending on the situation. Many methods of estimating moisture content exist that express the result as a gravimetric equivalent, without having to laboriously cut and repeatedly weigh specimens. Some of these are discussed in Section 2.5.2.

2.5.1 Drying timber

Removal of water from timber is an important value added process in the lumber industry. As such, drying of fresh felled timber is well studied. Water exists in timber in three forms [58–60];

1. Free water
   - Water in a liquid state contained in the cell cavities
2. Bound water
   - Water that is chemically bonded to the cell wall molecules via hydrogen bonding between water and hemicellulose and non-crystalline cellulose.
3. Water vapour
   - Vaporised water as a result of drying.

Green timber can be as much as 200% free water by weight and, during drying, it is the free water that is removed first [56, 60]. The removal of free water has no effect on the timber dimensions or mechanical properties however, it has a marked effect on weight and therefore, transportation costs. The point at which all free water is removed from cell cavities and only bound water remains is referred to as the fibre saturation point (FSP) [58]. The FSP generally occurs at approximately 27-30% moisture content [56], although the exact value varies depending on the timber species [58]. Lowering the MC below the FSP is the process of removing bound water and water vapour from the timber. The removal of this water results in shrinkage of the timber as well as an increase in most mechanical properties [56], see Figure 2-5. Dimensional changes from shrinkage due to drying can be as much as 9.5% tangentially and 4.5% radially [56, 58]. Further reduction in moisture content also decreases the timbers' risk of decay due to mould growth and rot [61–63]. A moisture content of at least 22% is required for micro organisms to cause decay in timber [60]. As such, a MC of 20% is generally accepted as an absolute maximum since below this level the timber is not at risk of decay or mould [64].

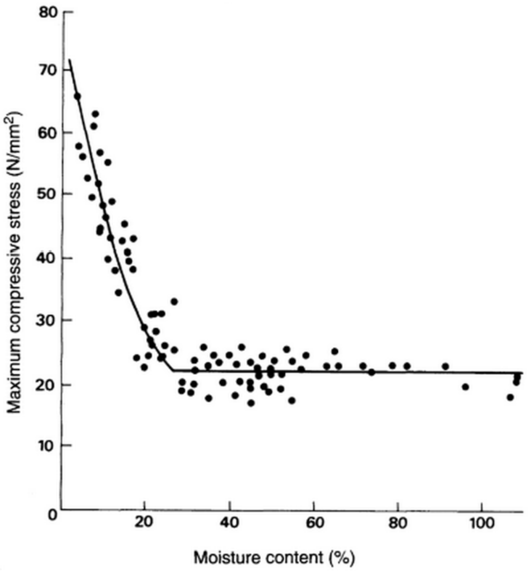


Figure 2-5: Relationship between moisture content and longitudinal compressive stress of timber. After the Fibre Saturation Point (FSP) is reached, strength increases as moisture content decreases. Figure from [56].

Drying may result in macroscopic physical changes to the timber, in addition to the expected dimensional shrinkage. Defects such as warping, splitting or collapse can occur if timber is dried too quickly or unevenly [58]. At a microscopic level, pit aspiration will occur, resulting in reduced flow paths within the timber [56, 60, 65]. Although the drying of timber is a complex heat and mass transfer problem, it can be described in relatively simple terms. Free water is removed from the timber by capillary forces. Moisture evaporates from fibres on the surface of the timber, creating capillary pressure that draws the free water out of the wood [60]. Bound water and water vapour diffuse through the timber, eventually evaporating from the surface. Diffusion of bound water and water vapour occurs simultaneously although the process is far faster for water vapour [60]. For moisture to evaporate from the surface, a pressure gradient is required. This can be achieved by reducing the humidity of the environment the timber is in [66]. If a reduced humidity is achieved, heating can help accelerate the drying process by increasing the energy available to the water for vaporisation. Care must be taken as excessive heat can damage the timber, as can drying too quickly due to low relative humidities [58, 64]. The effect of using excessive heat during drying can be seen clearly in the study presented in [67], where serious degradation in specimen strength was observed for specimens dried at high temperature (over 100 ^{0}C).

2.5.2 Moisture measurement techniques

The gravimetric moisture content of timber was defined by Equation 2.6 on page 39. This technique gives the "true" moisture content for the given volume of timber tested. This definition is used in BS EN 13183-1, "*Moisture content of a piece of sawn timber. Determination by oven dry method.*" [57]. The standard requires a sample of timber be cut from its parent for testing. For felled timber that is cut and stacked for drying, this method is appropriate however, for timber structures this approach may be impractical or inappropriate. For example, removal of specimens from historic structures may be prohibited. Removal of material from a structure may also compromise its mechanical properties if performed incorrectly. The oven dry method is also slow, taking at least 24 hrs to give a value for the timber moisture content. Instead, alternative methods of determining moisture content are available that measure material properties directly related to moisture content. The electrical properties of timber are strongly linked to its MC. The resistance can vary by orders of magnitude across all possible MC ranges and this relationship allows MC to be estimated via measurements of electrical properties of the timber [58]. Generally two types of electrical moisture meter are used for surveying moisture content; electrical capacitance and electrical resistance meters [68].

Capacitance type meters

Capacitance type meters are pin-less and non destructive. The meter relies on the relationship between MC and the dielectric properties of the timber. A known electrical field is generated near the timber surface and changes in the field due to the timber are measured. Changes in the field are related to the dielectric constant of the timber which is affected by moisture content. This change in field can therefore be related to the timber moisture content. The reading is an average moisture content for the volume of the electrical field generated by the instrument. Capacitance type moisture meters provide surface readings only. This type of meter is capable of reading MC to a value of 0% with diminished accuracy [69] although Eurocode 5 [57] recommends their use be limited between 7% and 30% MC. Readings are generally accurate to between ± 3% - ± 6% MC [70].

Resistance type meters

The resistance type moisture meter relies on the relationship between the electrical resistance of timber and moisture content, see Figure 2-6. As moisture content of timber increases, its electrical resistance decreases. Resistance type moisture meters exploit this relationship by forcing a known voltage between two pins that are inserted into the timber. The electrical resistance of the specimen is recorded and converted to an equivalent MC value. The value given is the lowest resistance between the pins across their entire depth in the timber. The relationship between moisture and resistance becomes less accurate at extreme highs and lows of MC. This is illustrated by Figure 2-6 which shows the exponential relationship between resistivity and moisture content for Douglas Fir.

At low moisture contents, the resistances that must be measured are high, leading to possible inaccuracies. At high MC, the gradient lessens, meaning small errors in measuring resistivity can lead to large errors in MC.

Timber has large natural variance in its properties which will affect its electrical resistance. As a result, the measurements from resistance type MC meters can be inconsistent from one specimen to another. Readings can even vary in the same piece of timber. This means that MC values from an electrical meter can have large confidence intervals. The report by Forsén et al. [72] found that for well conditioned specimens tested within a laboratory under strict environmental controls, the 95% confidence interval for measurement accuracy of a resistance type moisture content meter was 1.5 - 2.5 % units of MC. In industrial tests where the wood was not well conditioned and environment less strictly controlled, the

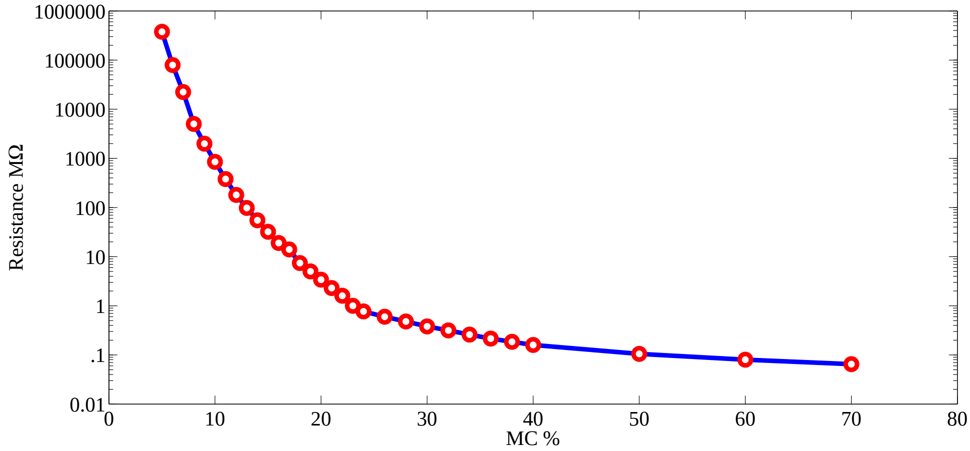


Figure 2-6: The relationship between electrical resistivity, (MΩ), and moisture content, (%), of Douglas Fir. The data is from an unpublished study by Edwards [71], reproduced by Blakemore [70].

accuracy of measurement was found to be 2.5 - 5 %. As such, the MC values produced by the meter are an estimate, subject to error and variance. They are not the "true" MC of the tested timber.

As noted in Publicly Available Specification 64: *Mitigation and recovery of water damaged buildings. Code of practice* (hereafter: PAS 64) [68], use of pin type meters limits the surveyor to surface or subsurface moisture readings. To detect moisture below the surface it is recommended to drill into the timber to the required depth and insert longer, insulated pins to obtain MC readings at the required depth. This process allows profiling of specimens to be performed, enabling identification of moisture gradients and possible trapped moisture within a structure. When surveying structures that have been exposed to flood water it is common to use a resistance type moisture meter with insulated pins and drill holes into the building fabric in order to assess moisture content at below surface depths [68]. The survey method is therefore semi-destructive as material must be removed to allow access to the meter pins.

Other measurement methods

Other methods of measuring moisture content such as thermographic measurement or the use of microwaves exist. They are less commonly used than hand held moisture meters due to their complexity of operation. A more thorough discussion of these methods can be found in [73] and [74]. There are also emerging methods of measuring MC discussed in Kidd et al. [73] and Phillipson et al. [74] such as Nuclear Magnetic Resonance (NMR) or advanced electrical arrays based on geotechnical survey equipment [75]. These promise the ability to perform detailed moisture profiling through a structure in a non-invasive or minimally invasive fashion. Electrical array methods similar to those developed by Sass and Viles [76], based on the premise presented by, amongst others, Kearey and Brooks [75] could, in theory, be applied to timber however, significant development work is required before such an approach could be reliably deployed to survey timber structures.

As for more advanced techniques; there is a large body of work relating to the use of NMR techniques to monitor the moisture content of timber. Studies such as Dvinskikh et al. [77] have used NMR to obtain moisture content profiles of timber samples. The use of NMR has allowed the researchers to observe, with great accuracy, how MC changes across the depth of a specimen. A similar study was performed by Araujo et al. [78]. Moisture distributions in specimens were resolvable to the scale of the growth ring and changes in MC across growth rings could be observed. An early investigation conducted at the start of this project was prompted by encouraging results reported in the literature. The results of this investigation led however, to the rejection of the technique as unsuitable for this project. The University of Bath's Chemistry department uses liquid state NMR machines. The investigation determined that the equipment was able detect the presence of water in samples of wetted timber dowel and produce crude moisture content profiles across the sample length. The equipment available requires samples to be < 4 mm Φ. When using small diameter dowel samples the machine size restrictions were not a limiting factor. However, as soon as an attempt was made to extract appropriately sized samples from specimens, problems were encountered. Due to the small size required, it was found that samples could not be removed from specimens without causing excessive friction. Both slicing and coring were trialled but the friction generated was sufficient to raise temperatures to approximately 80 ^{0}C. This increase in temperature due to the small specimen size required meant that there was no way to guarantee the specimen moisture content was undisturbed. In conjunction with the practical issues of obtaining samples, it was also found that without a prohibitively expensive upgrade of the University NMR equipment, data artefacts would be present that would make it impossible to interpret the MC profiles. These artefacts were caused by using the equipment in a manner it was simply not designed for. The specific functionality required for profiling moisture contents in timber specimens is not required for normal NMR use in chemistry. As such, it was determined that NMR was not a suitable technique for this project. It is more appropriate for situations where specimens can be carefully prepared and then forced changes in their moisture contents monitored using the technique.

Summary

Having rejected more advanced techniques, it is apparent that the most practical approach to moisture content measurement in timber is currently the commonly used resistance type moisture meter. It is a well established method, more accurate than the capacitance type moisture meter, is minimally invasive and can be used without requiring any sampling or development work.

The resistance type moisture meter allows for rapid measurements of multiple timber samples without the need to cut specimens, weigh and dry them; a process that takes a minimum of 24 hrs.

It is important to note that it is a technique that is not 100% accurate. The expected measurement inaccuracy could be as much as ±5% therefore, the MC readings must be treated as estimates of the moisture content.

2.5.3 Summary

Moisture content is an important factor in determining the mechanical properties of timber. Water exists in timber in three forms and its presence alters the weight and properties of the material. The Fibre Saturation Point (FSP) is the point at which all free water is removed from the timber. Moisture contents lower than the FSP result in an increase in most mechanical properties of timber. Drying of timber is achieved by lowering relative humidity and can be assisted by increasing temperature. Raising temperature too high or lowering the relative humidity too far can result in damage and defects in the timber as a result of drying too quickly and should therefore be avoided.

Many techniques exist to estimate the moisture content of timber however, the most practical and easily implemented is the resistance type, two pin moisture meter. It is commonly used, can be implemented immediately and recommended for surveying of flooded structures by PAS 64.

2.6 Timber frame and flooding

Timber frame is susceptible to damage from flooding in a way that many other construction types are not. This is true for the structure as a whole and for its individual component materials. As noted by Kelman and Spence [15], timber buildings are more buoyant than buildings constructed from other materials. Timber buildings are are therefore more likely to float or suffer from damage due to water uplift forces in a flood. The lightweight construction is also more likely to be damaged by water-borne debris in a flood, if present.

Flood water itself will also have an effect on timber frame. Timber is a natural, hygroscopic material that responds to moisture exposure differently to other construction materials such as steel, concrete or brick. Under normal conditions, timber and timber products gradually absorb and desorb moisture in the form of water vapour from the atmosphere until the timber reaches Equilibrium Moisture Content (EMC) [56]. At the EMC, the moisture content is in balance with the external environment. The equilibrium moisture content is a function of temperature and relative humidity of the environment the timber is in [58]. Thus, timber products will have a constantly changing MC depending on atmospheric conditions. Timber and timber based products show hysteresis when adsorbing and desorbing moisture.

An example of this behaviour is illustrated in Figure 2-7, taken from [79]. As relative humidity changes, so does the moisture content. Hartley et al. [79] test boards with two different resins (phenol formaldehyde (PF) and diphenylmethane diisocyanate (MDI)) and show that the resin used in the OSB makes little difference to its isotherm. The isotherm can be used to determine the EMC of the OSB in different relative humidity conditions.

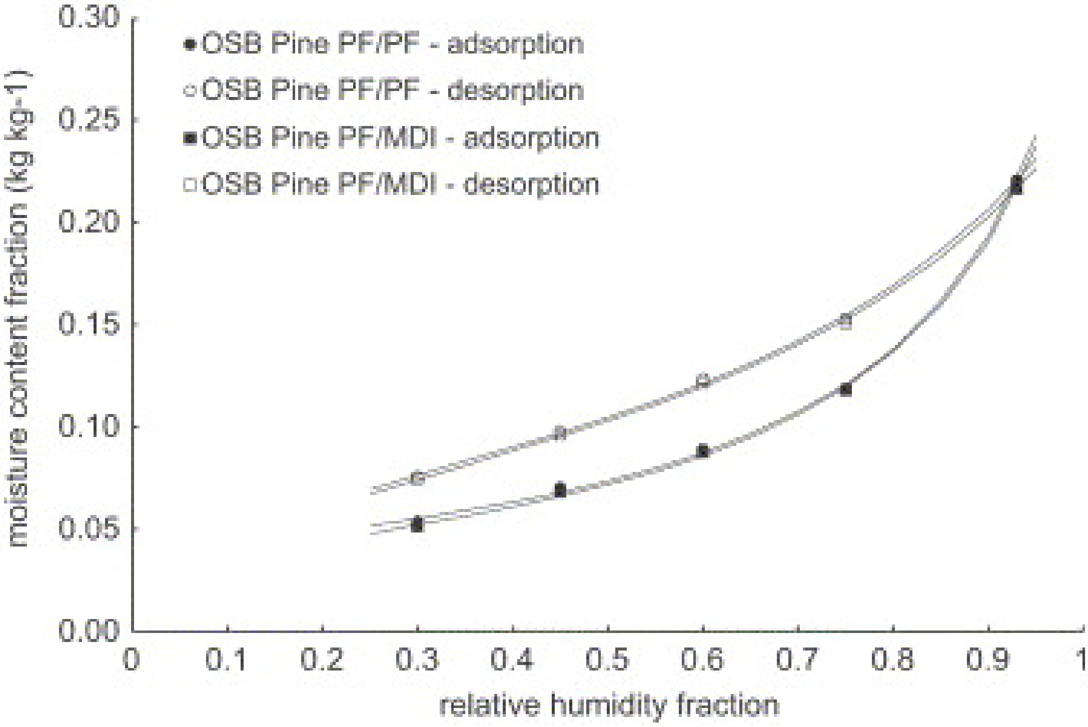


Figure 2-7: Adsorbtion and desorption isotherm for OSB from [79]. The difference in resins (phenol formaldehyde (PF) and diphenylmethane diisocyanate (MDI)) in the board has little effect on the water sorption behaviour.

This sorption behaviour is expected and is generally of little consequence to the structure beyond subtle effects such doors expanding in their frames. These effects are easily minimised by careful drying to an appropriate MC level before installation.

In contrast, exposure to liquid water causes a rapid change in MC and the moisture content can quickly increase beyond the FSP. As mentioned briefly in Section 2.5, up to the fibre saturation point, increasing MC will result in dimensional changes and a reduction in mechanical properties. Beyond the FSP, the additional water present increases the likelihood of decay. Thus, exposure of timber frame to flood water has a number of consequences.

- The structure will suffer a rapid increase in MC, leading to a reduction in mechanical properties.
- Dimensional changes in the form of swelling will be present, potentially loosening joints.
- The structure will become more susceptible to decay and mould growth, especially if the elevated MC is maintained for prolonged periods.

2.6.1 Component material tests

Results of tests on individual component materials of timber frame construction confirm the detrimental effects of elevated MC in timber and timber based products. The relationship between timber properties and moisture content is well documented. The chart by Dinwoodie [56], reproduced in Figure 2-5, page 41, shows the relationship between longitudinal compressive stress and moisture content. The increase in strength as the moisture content decreases is well defined.

The relationship between MC and strength exists in reverse too. Wetting of timber will decrease its strength properties. At increased moisture contents, a significant reduction in dowel bearing strength of timber is reported by Rammer and Winistorfer [63]. Figure 2-8 shows the effect of increasing MC on the mean dowel bearing strength (DBS) of clear southern pine. The loss in DBS is obvious; even relatively small increases in MC can result in large reductions in strength. Test data for other timber species also reported by Rammer and Winistorfer [63] show the same effect as seen in Figure 2-8.

Similarly, wood based products such as the OSB used for sheathing have been shown to suffer reductions in their mechanical properties due to increases in MC. For OSB used in sheathing, Wu and Suchsland [80] report losses in the modulus of rupture (MOR) and modulus of elasticity (MOE) in both parallel and perpendicular directions. Figure 2-9 shows the loss of MOE and MOR in both principle directions. An increase in MC from 5% to 20% corresponds to a loss in MOE of approximately 60% and a loss of approximately 50% MOR. This loss in strength is due to the swelling of the fibres that make up the OSB. The

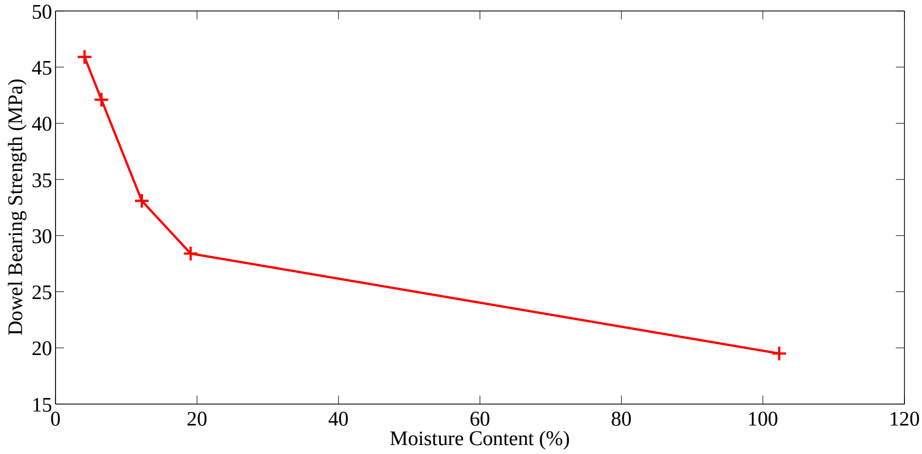


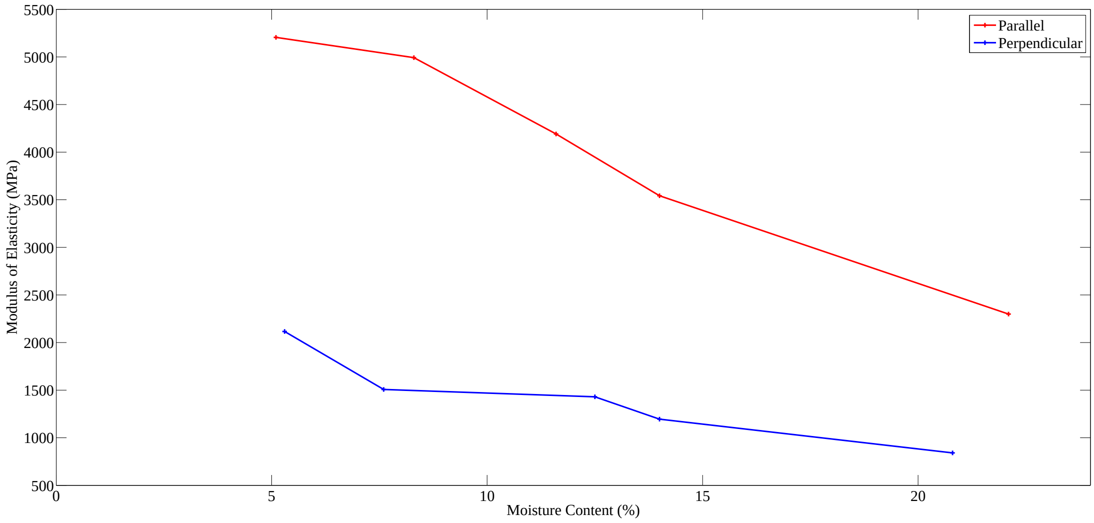
Figure 2-8: The effect of timber moisture content on the dowel bearing strength of clear southern pine. Data from [63]. Note the similarity between this chart and Figure 2-5, page 41.

swelling is sufficient to rupture the bonds between layers in the OSB. According to Wu and Piao [81], the swelling that results in this bond breakage is partially unrecoverable.

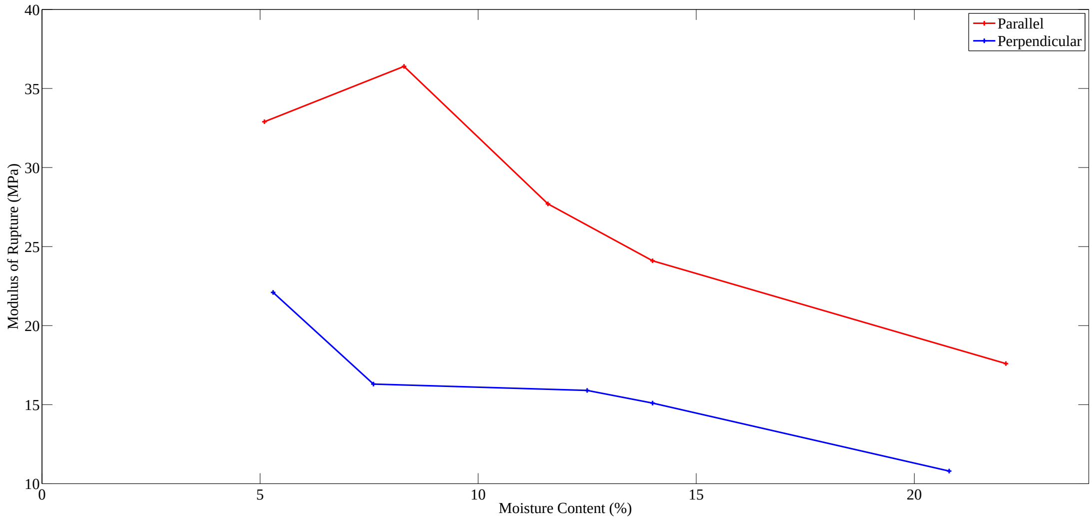
Similar findings are presented by Ang [82]. OSB was tested after exposure to liquid water for different time periods. A loss in embedment strength was also recorded. The embedment strength of un-wetted OSB fell from 46.6 MPa at 8% MC to 13.8 MPa at 77% MC. This is a reduction of approximately 70%. The embedment strength did not return to its original value after drying. The dried specimens had a mean embedment strength of 25 MPa. This represents a loss of 46% and is due to the same mechanism reported by Wu and Piao [81]; swelling causes the adhesive to rupture.

The embedment strength of C24 timber was also tested by Ang [82]. Embedment strength decreased by approximately half when wetted to 60% MC. Unlike the OSB, the timber tested was found to return to its original embedment strength after being dried. These results support assertions in various guidance documents [83, 84], that the timber framing is generally flood resilient and that it is the sheathing materials that tend to suffer from flooding.

Higher moisture content also increases the risk of mould and rot in timber [61–63, 85] and the longer timber has an elevated moisture content, the greater the risk



(a) Change in MOE of sheathing OSB as MC increases.



(b) Change in MOR of sheathing OSB as MC increases.

Figure 2-9: Change in mechanical properties of OSB sheathing as MC increases. MOE and MOR both decrease as MC increases. A change from 5% to 20% MC corresponds to approximately 60 % and 50% reductions in MOE and MOR respectively. Data from [80].

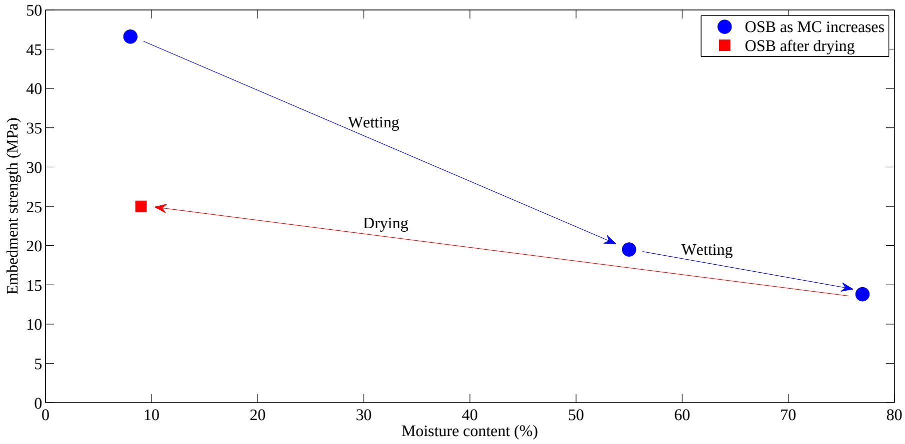


Figure 2-10: Embedment strength of OSB when wetted. The circular data show the progressive loss of strength as moisture content increases. The square data shows the strength after drying. The loss in embedment strength is significant and permanent. Data from [82].

of damage from decay [85]. Flooding also poses an environmental risk. Prolonged periods of high MC make timber prone to mould growth which can be damaging to occupants heath. Various studies have found links between increased mould growth due to dampness caused by flooding and a decrease in respiratory health of occupants [86–89]. The World Heath Organisation (WHO) also note that the most important trigger for growth of micro-organisms is the amount of water on or in materials [88]. A more through review of the health impacts of flooding is reported by Taylor et al. [89] however, the specifics are beyond the scope of this project. In addition to air quality issues, flood water itself poses a risk. Flood water is very often contaminated and even after it recedes, biologically harmful contaminants can remain [15]. Flooding therefore has the potential to severely affect the health of building occupants as well as potentially causing permanent damage to the structures component materials.

It is not just the process of wetting that is potentially damaging to a timber structure. As was discussed in Section 2.5, drying timber improves its mechanical properties however, there is a risk that if not dried correctly the timber may suffer adverse affects. Poor drying caused by incorrect drying conditions may result in defects such as splitting, checking, collapse or warping [58, 62, 64]. Changes in timber dimensions due to swelling and shrinkage may also lead to a loosening of the connections between timber members and between the timber and sheathing. This has the potential to reduce the stiffness and strength of the structure. There is also a risk that the mechanical fasteners in a timber frame could be compromised as a result of prolonged exposure to moisture. Although galvanized nails are specified [39], there is still a risk of oxidisation and a subsequent reduction in strength if exposed to moisture for prolonged periods of time. Oxidisation can also contribute to dimensional changes, exacerbating loosening of joints. Figure 2-11 shows corrosion beginning to occur on a galvanised nail after just seven days of submersion.

Figure 2-11: Galvanised nail showing the effects of submersion in water. The nail is beginning to show signs of corrosion after seven days of submersion. This is despite the fact galvanised nails were used. Image courtesy of [82].

2.6.2 OSB Grading

OSB is made of flakes of softwood layered in alternating orientations that are pressed under pressure and temperature to form a board. The flakes that make the board are bound together in a matrix of resin such as phenol formaldehyde (PF) or diphenylmethane diisocyanate (MDI). There are four grades of OSB as defined by BS EN 300 [90]. Their descriptions are given in table 2.2.

OSB/3 is the grade used in the construction of timber shear walls. BS EN 300 specifies the required thickness swelling of the boards after immersion in water. For 9 mm OSB/3, the standard specifies that the board should have a

Table 2.2: Descriptions of OSB Grades as given by BS EN 300 [90].

Grade	Description
OSB/1	Non load bearing boards for use in dry, interior conditions.
OSB/2	Load bearing boards for use in dry conditions.
OSB/3	Load bearing boards for use in humid conditions.
OSB/4	Heavy duty load bearing boards for humid conditions.

maximum swelling of 15% of the board thickness. The expected performance of OSB according to [90] is a useful indicator of the performance of OSB performance during flooding.

2.6.3 Summary

Each of the components of a timber shear wall is in some way susceptible to damage from flooding. As shown in this section, the process of wetting and drying causes changes in the mech anical properties of individual components of shear walls and in some cases, permanent reductions in the mechanical properties of the constituent materials result.

Where flooding is involved, there are environmental concerns too. The long term heath of occupants can be negatively impacted by effluent brought in by flood or by the risk posed by damp conditions.

Based on the behaviour of timber frame component materials exposed to elevated moisture contents, it would be reasonable to expect detrimental effects in timber frame as a result of exposure to flooding. Permanent losses in the mechanical properties of assembled frames should be expected after wetting and drying. Permanent losses in mechanical properties are more likely in the OSB sheathing of a shear wall than in the timber. When wetted, both lose embedment strength, but only the timber appears to regain it after drying. As will be shown later in Section 2.8 however, it is an area that has been subject to very little research and is poorly understood.

2.7 Existing flood repair guidance

Given the high risk and high cost of flooding, numerous guidance documents exist detailing how to recover property after flooding. These documents, as will be shown in this section, vary in scope and detail. The basic flood recovery process is a seven step framework, given by Garvin et al. [66]:

1. Conduct a full risk assessment.
2. Be aware of the direct and indirect health effects of flooding.
3. Decide method for disposal of remaining water and extract the bulk of the the water.
4. Assess flood damage to the building contents and manage as appropriate.
5. Decontaminate building in accordance with guidance
6. Dry building out until moisture content of materials reaches an appropriate level.
7. Fully document the making safe, decontamination and drying activities. Conduct a post flood survey of the building.

From this basic process there is only one stage that specifically deals with drying the structure, Step 6. The other stages are primarily concerned with the preparation for, and documenting of, the drying. Correct preparation, recording and reporting of the flood repair process is beyond the scope of this project and is well covered by PAS 64 [68].

For the purposes of this thesis, it is assumed flooding has occurred therefore, the stage of recovery that is of interest is number 6. For structures, Kidd et al. [73] define three basic types of drying; natural drying, convection drying and drying by dehumidification. The three methods are not mutually exclusive; it is accepted that they can be used in combination with each other as appropriate and that generally, assisted drying of some sort is preferred over natural drying [66, 91]. Guidance relating specifically to the drying of structures is however, lacking. A common theme with much of the available guidance is its general nature and lack of specific detail with respect to housing type and drying methodology. Guidance that deals explicitly with timber frame is even more scarce. A number of guidance documents are compared in Table 2.3 on page 57. Detailed reviews of available flood guidance have been compiled by Kidd et al. [73], and Lamond et al. [91].

It can be seen from Table 2.3 that the available documents offer very similar advice on drying, none of which is particularly specific. This similarity is also noted by Lamond et al. [91]. Generally it is suggested that if natural drying is to be used, the windows be opened to allow ventilation. If the central heating system works and it is safe to do so, it is suggested the thermostat be set between 20-22 ^{0}C to aid drying. Use of additional heaters is suggested where it is not possible to use the central heating although no temperature recommendations are given. Finally, if dehumidifiers are to be used, it is recommended that the structure have the doors and windows closed. There is no information given on what approach works best in a particular situation or for a particular structural type. Almost universally, no specific information is given on how to dry via mechanically assisted methods. Rarely is advice given that relates explicitly to just brick or just timber construction. The most detailed instruction with respect to drying are given by Garvin et al. [66], who recommend reducing the relative humidity to between 40 - 50%. Garvin et al. [66] also state that heating can speed up the drying process but that this is only effective if the humidity is controlled effectively. This is the only example of prescribed environmental conditions for drying in the literature and is broadly in agreement with drying recommendations for lumber [58, 60, 64]. Prevalent amongst various sources of guidance is the advice that any damaged internal surfaces, fixtures and fittings should be stripped out. With respect to timber frame structures, this involves the removal of plasterboard and internal sheathing to allow contaminated insulation to be disposed of. Wet insulation materials are very difficult to dry and slow the drying of the rest of the structure [92]. Their presence when wet will increase the likelihood of mould growth and rot. This process also makes the process of removing contaminated water from the structure simpler. The stripping out is limited to the internal face of the wall as it is impractical to remove the sheathing on the cavity side of the wall. The "dry" criteria for timber frame is given as approximately 20% MC in most cases. As previously noted, this is the moisture content level at which the risk of decay is reduced to an acceptable level [60, 64].

Table 2.3: Comparison of different drying guidance documents. The advice given has been separated into general and timber frame specific advice. The information given is limited in scope and does not explicitly state the best methods of drying a particular strucutre.

Document title	Year	Drying guidance	Timber specific guidance
BRE Digest 163 Drying out buildings [93]	1974	- If using natural drying, open doors and windows. - If using dehumidifiers, close windows. - Dehumidification is made more efficient with heaters.	- Timber should be dried to 10 - 12% MC.
BRE Good Repair Guide 11 - Part 1 (Immediate action) [94]	1997	- If using natural drying, open doors and windows. - Speed up drying by heating the building. - If safe to do so, set thermostat to 22 ^{0}C. - Alternatively, use an industrial heater. - Remove damaged plasterboard.	No
BRE Good Repair Guide 11 - Part 3 (Foundations and walls) [85]	1997	- Dry using ventilation and central heating. - Set thermostat to 22 ^{0}C or above. - If the central heating is not working, use portable heaters or dehumidifiers.	- Expose timber up to the water level. - Remove plasterboard, sheathing, linings etc... - Remove contaminated insulation - Check racking resistance and fix OSB to internal face if required. - Dry to 20% MC. - The bottom rail may take longer to dry
Standards for the repair of buildings following flooding [73]	2005	- Optimum relative humidity is 40-50%. - Heating can increase the rate of drying. - Heating is only effective if relative humidity is controlled. - If safe to do so, set the thermostat to 22 ^{0}C. - Removal of moist air is important to the drying process.	- Remove,contaminated surface finishes. - Remove debris deposited in frame. - Remove contaminated insulation. - Dry rot of timber is a risk if not properly dried. - Dry below 20% MC.
After a flood: Practical advice on recovering from a flood [95]	2007	- Pump out water. - Remove mud and debris. - If using natural drying, open doors and windows as much as possible. - If using dehumidifiers, close doors,and windows.	No

The updated industry standard guide, PAS 64 [68] provides recommendations and guidance for the restoration of water damaged buildings. PAS 64 is intended to be an industry "best practice" guide. It takes the user through from the initial incident to the point at which the repair and reinstatement process can commence. The preparation and recording of work laid out in the seven step framework given earlier is covered in detail by PAS 64. Detailed information on measuring moisture content is provided, as is a comprehensive description of many types of drying apparatus available and how to operate them. Instructions for use and conditions at which various drying units operate most effectively are provided. PAS 64 does not however, offer recommendations on the best type of drying for a particular structure. This is left to the discretion of individuals or flood repair contractors. There is evidence that leaving this decision to individual firms, in the absence of robust guidance, leads to variations in approach, even for properties of the same type [16].

The brevity and simplicity of guidance documents such as those compared in Table 2.3 is somewhat necessary; they must be immediately accessible to the user in the event of a flood. A multi-page, detailed technical report is inappropriate, thus short concise documents are often produced. Part of the lack of detail in the available guidance however, is due to a lack of research.

A good example of the lack of research is the mapping of drying method to structural type. The lack of specific mapping of housing type to drying methodology was identified by Garvin et al. [66]. The same thing was once more identified as lacking five years later by Kidd et al. [73] and then again four years later by Lamond et al. [91]. This particular issue, although identified numerous times, has gone unaddressed for a decade. As such, guides like PAS 64 that attempt to be authoritative cannot. There is simply not sufficient evidence base available to work from. This lack of research is perhaps understandable, it is noted by Taylor et al. [96] that the "*Constructing of physical structures is expensive, time consuming...*" and that experimentation concerning flood drying is "*...limited to testing a single scenario at a time...*". A direct reflection of the difficulty in testing is the fact that Taylor et al. [96] reference just four examples of physical tests of flooded structures.

Expert perceptions

Not included in Table 2.3 is the 2008 study by Proverbs and Soetanto into the perceptions of flood repair experts [16]. It is not included in the table as it is not strictly speaking, a guidance document however, the results are particularly interesting. The results of the study suggest that many flood repair experts will consider using "*...various methods to assist drying, rather than focus on a single dominant method*". It was found that the majority of respondents would not change their current approach to drying, even if they were allowed to do so. Much of the guidance in Table 2.3 suggests using the central heating system to aid where safe to do so, however, Proverbs and Soetanto [16] found this to be the least popular method amongst the experts surveyed. Use of artificial heating systems was the most popular method; natural ventilation, aided air circulation and dehumidification were found to be approximately equally popular as one another. The respondents were also asked about the moisture monitoring techniques they employed, with 79% stating that they used visual inspection, despite also reporting this to be the perceived joint least effective method. The study suggests that for many flood repair practitioners, drying is not a "*scientific process, but one of experience and subjectivity, the reliance of which must be doubted*".

It is clear that there is much confusion surrounding the drying process following flood. The guidance available is limited and non-specific. Furthermore, there is little consensus even amongst professionals and experts as to the best course of action. Professionals are often reliant on subjective judgements and experience over evidence when drying properties.

2.7.1 Drying times

One of the most common questions with respect to flooding concerns the length of time it will take to dry a building. The time taken to dry a structure following a flood varies by a large amount [73]. Figure 2-12, from Kidd et al. [73], shows drying times for all types of properties following the summer floods that affected the UK in 2007. A large range of times, from days to months, is clearly visible.

Lack of research may well be a contributing factor in the variation in length of time it takes to dry a structure. The Pitt review noted after the 2007 floods that, with respect to drying, "*... cases of undue delay may be due to the absence of definitive guidance about drying methods*" [3].

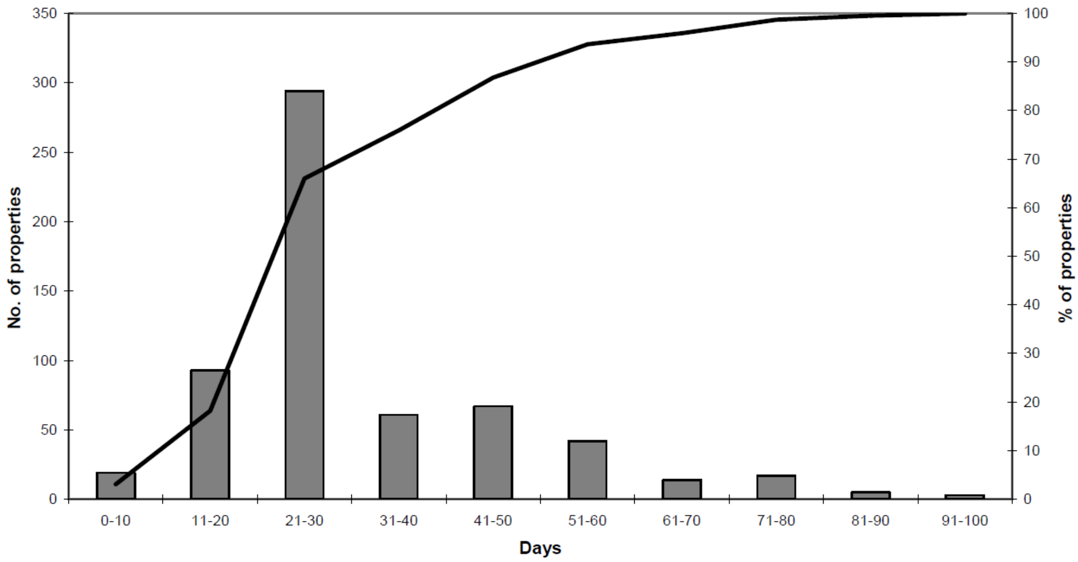


Figure 2-12: Range of drying times of properties flooded during the summer 2007 floods. The chart is from [73] and uses data from the National Flood School.

Figure 2-12 shows a range of drying times up to 100 days for the 2007 summer floods. The time taken to dry a structure and reinstate the occupiers is clearly an important issue. Many people expect the repair and reinstatement process to be achieved within six months even though the Association of British Insurers suggest 12-18 months is more likely [91, 97].

Drying time is also an issue that is strongly linked to the mapping of drying method to the structure type. Home owners have reported having the drying process repeated as it was done incorrectly in the first instance [3, 91]. Despite public expectations, arguably the time taken to dry is less important than the potential effect of flooding on the mechanical properties of the structure. Clearly it is unsafe to have a structure that is dried quickly after a flood but has compromised load carrying ability. This is of particular concern with timber frame due to the way the mechanical properties of its components change when exposed to elevated moisture content.

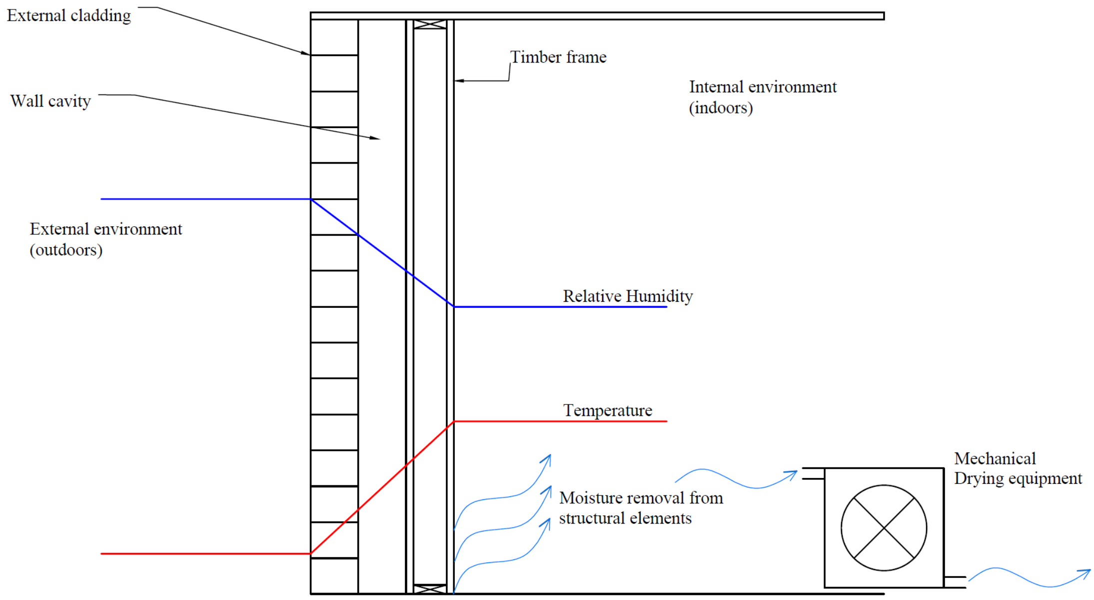


Figure 2-13: Simplified drying boundary conditions in a real structure. The structure is dried using a controlled environment on the inside. This exposes the structure to two different environments which influence the drying. These boundary conditions are challenging to reproduce accurately in the laboratory. Temperature and relative humidity are indicative only, they are not meant to accurately represent real variations through a structure.

Another reason to move away from drying time as a standard measure of flood recovery efficacy is the difficulty in simulating it accurately in the laboratory. In a real structure with external cladding, wall cavities, insulation etc... the structure is exposed to multiple drying environments with complex moisture escape routes. In a wall for example, the internal face is in a controlled drying environment whereas the external face is exposed to whatever conditions prevail in the wall cavity. The cavity conditions are influenced by the external environment as well as the internal. Example drying boundary conditions and variations in possible drying environments are illustrated in Figure 2-13. Boundary conditions also vary between structures depending on specific construction details, making them difficult to accurately recreate in a laboratory. The difficulty in accurately recreating the boundary conditions such as those illustrated in Figure 2-13 mean that measured drying times from laboratory experiments are unlikely to be representative of a real structure. This, combined with the potential loss in mechanical properties a timber structure could face as a result of flooding, means that a change in the focus of drying from time to structural properties is justifiable.

2.7.2 Summary

This section has provided a comparison of some of the existing flood guidance available. It has been shown that much of it is basic and lacks in detail regarding to how to dry a structure. Review studies such as the one by Lamond et al. [91] have shown much of the advice to home owners to be contradictory, as well as identifying several gaps in the guidance. In fact Lamond et al. [91] suggest that new guidance, with knowledge gaps addressed, would be welcomed by the industry. Issues, such as mapping building type to drying methodology, have been identified numerous times by researchers and yet still have not been addressed. This lack of research is even more glaring with respect to timber frame. The effect of this lack of research is seen in the guidance available and arguably in the range of times taken to dry and reinstate occupants to a structure. It can also be seen in the subjective approach taken by many professionals as reported by Proverbs and Soetanto [16]. Although time taken to dry is an important factor, given the potential detrimental effects flooding can have on timber frame, the effect on its mechanical properties should be considered. Therefore, mechanical properties, rather than time taken to dry, should be monitored as an indicator as to the effectiveness of different drying methods.

2.8 Experimental studies on flooding

It was shown in Sections 2.5 and 2.6 that the mechanical properties of timber frame components were likely to be adversely affected by elevated moisture content due to flooding. Section 2.7 demonstrated that research into flooding and its effects on buildings is limited. Research specific to timber frame is rare, as is research focused on the effect flooding has on mechanical properties of a structure. In this section, the small number of relevant studies the author was able to locate are evaluated. Studies are presented in chronological order.

2.8.1 Pace 1988

The study by Pace [98] was produced for the US Army Corps of Engineers and investigates the effect flooding has on a series of construction materials and systems. Full sized, brick and concrete block walls were tested with water loading on one side. In addition, a full sized home was flood tested.

The wall tests were performed to determine at what flood depth walls were at risk of collapse. Flooding on one side creates a push over force from the water. It was found that a flood depth of 0.61 m (2 ft)[1] was the point at which the walls began to behave plastically; small depth increases led to large increases in deflection. At flood depths of between 0.73 m and 0.91 m (2.4 ft and 3 ft) the walls suddenly collapsed. The wall deflections at collapse were small, approximately 0.025 cm to 0.051 cm (0.01 inches to 0.02 inches). Walls suffered significant damage at small deflections and were liable to sudden collapse. The walls were tested without return walls in place, reducing their loading capacity.

The full sized house that was flood tested was located in Arizona and had previously been vacated due to flooding. The aim of the test was to determine the practicality of protecting the house from flood water using sheeting attached

[1]Original study used US Imperial units. SI conversion is approximate.

to the house and to substantiate the earlier results with regards to safe levels of flooding. An earth berm was constructed around the house and the level of flood water slowly raised. The house was protected from the flood by the plastic sheeting system being tested. The results showed that the house could withstand approximately 0.91 m (3 ft) of water head without damage however, at a depth of 1.22 m (4 ft), damage was suffered. The unloading curves for the house show that permanent damage had occurred due to the water loading.

Although this study did not focus on timber frame explicitly, it draws a useful general conclusion; water loading on a single side of a structure can cause significant damage. Attempting to exclude water from a structure can lead to dangerous loads that can cause sudden collapse. The deflections associated with these loads are small and difficult to observe without monitoring equipment. The author noted that it is better to allow flooding to occur and then repair a structure than attempt to exclude water entirely, have uneven loading on the walls and risk potential collapse. These results for flood height and collapse risk have been used as the basis of a number of subsequent studies according to Kelman and Spence [15]. It is worth noting that the critical water heights recorded here are for single sided loading on a structure. This creates a large push over force on the walls tested. In a flood where water enters a structure, the relative pushover force is reduced by the water on the inside resisting the force of the water on the outside. In such cases, the critical depths suggested by Pace [98] may be greater.

Pace also notes the difficulty of attempting to exclude water entirely from the test house and from some small scale tests conducted. When testing various coatings and exclusion systems, the author found it was exceptionally challenging to keep any moisture from entering the test structures. A similar finding is reported by Aglan [99] 17 years later, see Section 2.8.3.

2.8.2 Leichti et al. 2002

The conference paper by Leichti et al. [100] investigated the load capacity of OSB sheathed timber shear walls subjected to simulated flooding. Walls were weighed then soaked for seven days at a depth of 1 m. The walls were then dried naturally until they had reached within 3 kg of their original mass. The reason for the criteria of 3 kg is not given and only natural drying is investigated. Separate specimens of the OSB sheathing were also cut and soaked in order to perform material property tests to assess the shear and embedment strength of the OSB.

The wetted OSB showed a maximum loss in embedment strength of 14.17 MPa; 35.3 MPa when dry and 21.2 MPa at its weakest after wetting. This is equivalent to a 40% reduction in the original board embedment strength. Maximum loss of shear strength was approximately 30% in both both board orientations. The shear walls were subject to monotonic and cyclic loading, in both cases without applied vertical loads. It is assumed that the hold down arrangements make the walls equivalent to fully anchored walls however, this is not clear from the paper. The results from the monotonic tests indicated that mean capacity of the walls was not reduced by water exposure. The only mechanical property reported to have decreased was stiffness, for which a 27% reduction was observed. The authors concluded that walls inundated with fresh water and dried "*expediously*" do not not experience a loss in lateral capacity but will suffer a loss in stiffness.

The methodology in the paper is not particularly clear; it is difficult to determine exactly how walls were tested and which data relates to control walls. It is also difficult to determine which data related to flooded walls tested monotonically or cyclically. In addition, the type of OSB used is not stated and the hold down arrangements for the wall are unclear.

The results of this paper are unexpected. Outcomes of the material testing performed on the OSB are different to those reported in [80, 81] and [82]. The reduction in mechanical properties is far less than would be expected for a moderate rise in MC. Wu and Suchsland [80] an increase in MC to just 20% resulted in a 60% reduction in MOE. For OSB with a MC elevated above the FSP, Ang [82] reported losses in embedment strength of approximately 70%. The lateral capacity of the walls tested after flooding was in fact slightly greater than that of the control condition and with reduced variation; 30.6 kN (12%) and 26.8 kN (6%) respectively. Given the permanent effects of water exposure on timber and OSB discussed in Section 2.6, a loss in the load carrying capacity of the shear wall would be expected.

Based on a comparison of the material tests performed in this study and from other work, the results presented here are surprising. A more dramatic, permanent reduction in OSB properties would be expected, as would a reduction in the mechanical properties of the wall. The reported increase in wall capacity is therefore surprising.

2.8.3 Aglan 2005

The study by Aglan [99] investigated the effect of flooding on typical US home constructions subject to flood. Due to the cost of testing full size dwellings, a series of "*proto-typical*", 2.44 m $\times$ 2.44 m (8 ft $\times$ 8 ft)[2] modules were constructed. Baseline behaviour was established by testing modules constructed from timber stud work with plywood sheathing and either plywood siding or hardboard lap siding. Further test modules were then modified in an attempt to make them more flood resilient. It is mainly the baseline behaviour that is of interest here. The test modules were flooded to a depth of 0.61 m (2 ft) before being naturally dried for 28 days. The modules were then disassembled and tested.

Samples of the plywood sheathing were cut and subject to three point bending tests in order to determine flexural strength and flexural modulus . It was found that, for specimens from below the water line, there was no significant change in the mechanical properties compared to those specimens from above the waterline. With respect to moisture content, the modules did not return to their original moisture contents although the units with hardboard lap siding had a lower MC than those with the plywood siding. It was assumed that the plywood siding trapped more moisture than the hardboard lap siding, hence the higher MC. The report found that the timber stud work in the test modules could be considered flood resistant as long as it was dried to normal moisture levels.

This study is interesting as it closely mimics a domestic dwelling. The use of plywood instead of OSB reflects the geographical location of the study. It was found that the plywood trapped moisture, leading to increased risk of mould and rot however, it retained its mechanical properties in a way that OSB sheathing, based on the studies discussed in Section 2.6.1, does not appear to. The structural behaviour of the walls was assessed only via material properties of the individual

[2]The original study used US Imperial units. SI conversion is approximate.

components, whole modules were not assessed for load resistance. Furthermore, the study only investigated natural drying, not mechanically assisted drying.

One important finding was the difference using different wall materials and construction details made to the flood performance of the test modules. The use of hardboard lap siding instead of plywood siding led to less moisture being trapped in the wall. This has important implications for the choice of materials and wall layouts used in flood prone areas. Care must be taken to ensure that material choices and construction details do not negatively affect flood performance, especially by inadvertently trapping moisture or by restricting drying surfaces in a structure. Finally it is worth noting that the study concludes that attempting to entirely flood proof a structure is not a viable approach. In a second part of the study assessing various flood proofing techniques, despite attempts to entirely exclude water during soaking of the test structures, modules still flooded. This is similar to the findings reproted by Pace [98], Section 2.8.1; water is exceptionally difficult to fully exclude from a structure.

2.8.4 Lambert 2006

The study by Lambert [101] was a commissioned piece of research into a commercial drying system. The company that originally commissioned the work, “Dryair” now trades as “Clearblue flood drying” [102]. The drying system is one which uses a heat exchanger to raise the temperature of the room to be dried. It is a “high temperature, high volume” drying system that lowers the relative humidity of a room by heating the air to between 50 - 70 ^{0}C.

The report states that the aim of the investigation was to assess the performance of the system at returning a range of water saturated building elements to an acceptable pre-flood condition. Three types of brick wall were tested;

1. Cavity wall with breeze block.
2. Cavity wall with concrete block.
3. Solid wall with reclaimed brick.

In addition, five types of timber element were tested. These were;

1. Hardwood external door
2. Internal pine door
3. Floorboards on joists; 1 m in length by 1 m in width
4. Skirting board
5. A wooden chair

A plasterboard panel was also tested.

The brick wall elements were soaked for five days using a high humidity mist room. The timber elements were submerged in a water bath for 48 hours. After soaking, all elements were transferred to a drying room, the environment of which was controlled by the proprietary heat exchangers being tested. Weight change, dimensional change and visual inspection were used to monitor the specimens.

The mass of the timber elements after drying was always less than the original mass, indicating that any moisture present due to soaking had been removed. Strain gauges on the wall specimens did not register strains in the range likely to cause damage.

Data for the timber specimens showed that they were more susceptible to warping and cracking than the masonry walls. The internal pine door tested showed signs of de-lamination of the hardboard facing after drying. The plasterboard panel was found to have distorted due to wetting. In addition it was noted that there was little distortion of the timber specimens apart from the pine door and the plasterboard.

The tests conducted do not directly assess the structural performance or mechanical properties of the materials. Visual inspection and dimensional changes are used to indicate whether the wetting or drying is likely to cause damage. The masonry elements are not unduly affected by the process. The timber elements showed a small amount of damage due to wetting and drying however, they were only soaked for a short period of time. The study is one of the few to investigate the effect of mechanical drying instead of natural drying. The applicability of the results to timber frame is limited as no structural timber elements were tested and no load tests were performed. There is some debate as to whether these so called speed drying methods are appropriate. It is suggested that they can be harmful to historic buildings and their use is not recommended [73, 103]. Practitioners of speed drying however, refute such claims[3] . Ultimately there is too little independent evidence available to reach a conclusion.

2.8.5 Escarameia et al. 2007

The study by Escarameia et al. [92] investigated multiple wall construction types. It is a publication produced through work conducted as part of a CIRIA project. The paper is based on the project lab report, see Tagg et al. [104]. For the research project, different wall types were fabricated with a range of external renders. A test tank was used to expose walls to simulated flooding on one the external face. The leakage rate through each wall during the wetting phase was measured. Time taken to dry under natural drying conditions was then recorded. It was noted that the natural drying of the test walls did not allow them to return to their pre-wetting moisture content within the six days allotted for the drying phase of the experiment. As a result, time to dry to original MC was extrapolated. The insulation in the walls was found to take months to dry and never fully recovered its original moisture content. When wet, the insulation materials also tended to slump to the bottom of the wall under their own increased weight. It was also found that the type of render on the wall affected the leakage and drying rate.

During the testing programme, the mechanical properties of the walls were not tested. The study also only investigated natural drying. Mechanically assisted methods of drying were not considered. The study does not consider timber specifically nor does it make investigation into the effect flooding has on the mechanical properties of the walls. Limited data is available on timber frame as the study primarily focused on the leakage rate of different renders. The study was concerned with categorising the suitability of different external construction choices for water exclusion during flood. One result of particular interest in this study is the effect of flooding on the insulation. The difficulty faced in drying insulation and its slumping behaviour when wet all help justify the advice to remove it after flooding and replace it once the rest of the structure is dry.

[3]Habbershaw, A. Personal communication (Email), 19th July 2012.

2.8.6 Bradley et al. 2014

The conference paper by the author (Bradley et al. [67]) for the World Conference on Timber Engineering 2014 (WCTE) studied the effect of different drying environments on sheathing to timber connections from a typical timber frame structure. The work served as a pilot study to the work presented in Chapter 4 in this thesis and to the related paper by Bradley et al. [13].

The WCTE paper reported investigations into the effect different drying environments had on the recovered mechanical properties of nailed sheathing to timber connections after immersion in water. Environmental extremes such as 105 ^{0}C were included in the study. A difference in recovered properties was observed for different drying conditions. All tested specimens suffered a loss in strength, stiffness and energy dissipation after being wetted and dried however, the drying environment used influenced the degree to which these properties were affected. It was found that specimens exposed to a "*...medium heat and low RH environment...*" [67], had the greatest recovery of mechanical properties. It was also found that the extreme temperature environment tested (100 ^{0}C and 0 %RH), resulted in the quickest drying but also the worst recovery of mechanical properties. This environment caused significant damage to the connections.

This work showed that the drying environment does influence the recovery of connection mechanical properties and that extreme drying conditions have the potential to cause significant damage to a structure. As noted in Section 2.5.1, highs and lows of temperature and relative humidity when drying are damaging. This work also supports the evidence in Section 2.6.1 that suggests, based on material tests, that timber frame will weaken due to exposure to flooding.

2.8.7 Bradley et al. 2015

The study by the author (Bradley et al. [13]) was a follow-on from the 2014 Bradley et al. [67] study. The work is also the basis for Chapter 4. It was further confirmed that drying environments affect the recovered mechanical properties of sheathing to timber connections and that an optimised drying environment could be determined. For further details, see Chapter 4.

2.8.8 Summary

The small amount of relevant research into the effect of flooding on the behaviour of structures has been reviewed. As was stated earlier, there is a serious lack of research into the effects of flooding on timber frame. It can be seen from the review that, apart from work conducted by the author during this research project, no systematic study into the effect of flooding on the mechanical properties of timber appears to exist. Similarly, no studies have attempted to determine the best drying methodology for timber frame, apart from those produced during this project. Timber, where it is considered, is often studied as a non structural element such as doors or floorboards, see Lambert [101]. The study by Leichti et al. [100] does treat timber as a structural element, but only investigates natural drying. The study by Leichti et al. [100] also reported surprising results that are in direct contradiction to tests on shear wall component materials. The study in the US by Aglan [99] provides interesting data regarding wall construction choices with respect to trapping moisture however, it does not directly address structural behaviour. Its focus on the US market and construction norms also makes it of limited use in a UK context. It is interesting to note that Aglan found plywood to be relatively flood resilient during his testing. The early study by Pace [98] established the limit of flood depth that can be sustained before sudden collapse occurs in structures. The limits are still used in current research according to Kelman and Spence [15]. The Pace study also noted that it is often better to allow flooding to enter a structure than it is to attempt to exclude it entirely. Both Pace and Aglan note how difficult it is to attempt to entirely prevent water ingress into a structure.

From the review it can be seen that there are no systematic studies that investigate the mapping of drying method to a building type. Either drying is restricted to natural drying or only a single environment produced by a proprietary system is investigated. Similarly, there are no reliable studies that investigate the effect of flooding on the mechanical properties of timber frame. The mechanical properties of the whole system are either ignored as criteria or are assessed via the mechanical properties of individual component materials. Whole structures, or full structural components are rarely subject to direct load testing. The one example of such a test by Leichti et al. [100], produced results that were in contradiction to what would be expected from existing data. As such, there is a need to address both the mapping of drying method to building type and the lack of understanding of how timber frame performs during flooding. Neither of these topics are sufficiently addressed by existing research and this lack of understanding impacts the quality of the guidance available.

2.9 Summary and conclusions

A number of important concepts have been explored in this Chapter. A definition of what is meant by timber frame (TF) was given and specific details regarding its use in the UK were also provided. The relationship between sheathing to timber connection strength and overall wall behaviour was explored. The application of this relationship to design code models was also discussed. The potential effects of flood on the component materials of timber frame were explored. From a review of previous studies, it was seen that all component materials of platform timber frame are in some way susceptible to flood damage.

Existing guidance for recovering after flood has been reviewed. It was shown that this guidance is lacking in detail as a result of a scarcity of research. A major unaddressed issue that has been identified by a number of researchers, the mapping of drying method to structural type, was also introduced. It was argued that, for timber frame, mechanical properties may be a more appropriate factor to monitor rather than drying time when it comes to assessing recovery from flood. Researchers have pointed out that new guidance that attempted to address these gaps would be welcomed by the flood repair industry. Finally, a review of experimental work into flooding and its effects on mechanical properties was undertaken. The studies are limited; other than those produced by the author of this thesis as part of the research project, most do not investigate different types of drying environment beyond natural drying. Timber is often assessed as non structural element. One study that relates directly to timber shear walls clad in OSB sheathing reported results that are in contradiction to the results of tests performed on the individual component materials of shear walls.

Within the UK flooding is still a major risk, and one that is only likely to increase in severity in the coming century. At the same time, the country faces a housing shortage. The urgent demand for more housing is likely to be met in part by timber frame. Timber frame has been growing in market share and given its environmental and economic credentials, this market share is likely to keep on growing. Many of these new timber frame houses are likely to be built on flood plains or in areas at risk of flooding [11]. The Pitt Report noted that although ideal, ending building on flood plains is unrealistic [3]. Despite the risk flooding poses, there is a serious lack of research and this is reflected in the guidance available to occupiers.

The key findings of this chapter are summarised below:

- Flooding is a major risk to the UK.
- The use of timber frame in the UK is increasing.
- There is an urgent need to construct more housing and this need will, in part, be met by timber frame.
- Much of this new housing will likely be at risk of flooding.
- It therefore follows that many timber frame structures will at some point experience flooding.
- Timber frame is susceptible to flooding;
  - It is more buoyant than other construction types.
  - The component materials experience a reduction in mechanical properties when wetted.
  - Incorrect drying via excessive heat or excessively low relative humidity has the potential to cause damage.
- There is a lack of guidance related to repairing timber frame after flood.
- There is a lack of research into the effect of flooding on timber frame.
- This lack of research has been identified on numerous occasions and needs addressed.

Returning to the thesis focus of resilience and repair of timber frame given in

Chapter 1, it is clear from the evidence available that there is a poor understanding of both. Given the risk of flood and the likely increase in timber frame usage, more research is needed in order to quantify the effects flooding will have on timber frame. This thesis therefore aims to begin addressing this lack of research via an experimental approach. Guidance is lacking and there is very little data on the performance of timber frame during and after flooding. The only dedicated study, by Leichti et al. [100], is contradictory to the results of materials tests.

In order to construct buildings that are more flood resilient, an understanding of current performance is required. As current understanding is not sufficient, one of the main themes of this thesis will be to investigate how timber frame structures respond to flooding and drying. The other focus will be an investigating into how to effectively dry timber frame after flood. This is important as it is an area where potentially permanent structural damage could occur during the recovery from flood if not performed correctly.

Chapter 3

Methodology

In this Chapter, the research methodology is presented. In Chapter 2, two main areas of research interest were identified; mapping drying methods to structural type and addressing the lack of data regarding timber frame and its structural behaviour during and after flood. From Chapter 2 it can be seen that flooding presents a clear danger to timber frame structures. Increases in moisture content will lead to reductions in the mechanical properties of the component materials, especially the OSB sheathing. Timber buildings with elevated moisture content levels are also at increased risk of mould and rot, even after flood waters have receded. In addition, it was found that drying of timber frame has the potential to cause damage to the structural materials if carried out incorrectly. A review of the existing literature found very little research concerning timber frame and flood. This is reflected in the lack of clear guidance available. The response of timber frame to flood has never been adequately established. The research in this thesis aims to address this.

This study takes a multi-scaled, experimental approach to understanding how timber frame responds to flood. Drying performance and structural response are both investigated, with results used to develop a better understanding of the response of timber frame to flooding.

3.1 Research aims

Based on the literature review and within the project scope of resilience and repair, two important areas of research were identified; the mapping of drying method to structural type and addressing the lack of data regarding timber frame and the changes in its structural behaviour due to flood. The thesis therefore has the following two research aims:

1. To identify an optimum drying method for timber frame structures,
    - Do different drying environments affect the extent to which mechanical properties are recovered?
    - Can the drying environment be optimized for timber frame?
2. Assess the effect of flooding on the structural performance and mechanical properties of timber frame structures.
    - How does flooding affect properties such as strength, stiffness, and ductility?
    - How does drying after flood affect these properties in a structure?

The first aim will, in part, address the knowledge gap in mappping drying method to structural type identified by [66], [92] and [91]. The second aim will help to address the lack of research into the structural performance of timber frame during flood. Given the lack of existing data, there is little point attempting to improve the flood resilience of timber structures before their basic behaviour during and after flood is understood. Investigating methods of flood "proofing" or improving flood resilience have therefore been deliberately eschewed in favour of developing a baseline understanding of the effect of flood on the behaviour of timber frame.

3.2 Experimental approach

This project takes a multi-scale experimental approach. Connection scale tests and full wall tests are conducted in order to study the relationship between timber frame and flooding. In all experiments the same materials are used, namely:

- Sheathing
  - 9 mm OSB/3 produced by Norboard and supplied by a local timber merchant.
- Timber
  - Quarter sawn Douglas Fir; grown and processed locally in the South West of England.

Specimens that model the nailed connection between sheathing and timber frame are used to study drying environments in Chapter 4. Connection specimens are advantageous in that their small size makes soaking and drying multiple specimens with the equipment available at the university. To test an equivalent number of whole walls in the same way is not feasible. Given the limited project resources, constructing multiple connection models and testing them is more effective than doing the same for the equivalent number of shear walls. Multiple drying environments can be studied and optimum conditions identified based on the results of these tests. In addition, failure mechanisms of the nailed connection can be studied in detail. This is important as these connections govern much of the wall behaviour. The results of the connection tests are then used to plan shear wall tests.

Although there is a direct relationship between the connection properties and shear wall behaviour as discussed in Chapter 2, Section 2.4, not all wall properties can be determined from the connection. It is therefore necessary to perform shear wall tests.

In Chapter 5, shear walls are assembled and subject to slightly modified versions of standard racking tests. The behaviour of the walls before, during and after flooding is categorised, leading to a new understanding of the effect of flooding on shear wall performance. Structural performance is assessed and mechanical properties are calculated in order to derive a better understanding of how shear walls behave as a result of flooding. Testing of shear walls is necessary in order to understand how they perform as an entire structural system when under load. Connection tests do not reveal any information relating to load paths or failure mechanisms of the entire wall. For example, possible out of plane behaviours of the wall cannot be studied using only connection models, hence the testing of shear walls. The results from Chapters 4 and 5 are used to address the two aims stated at the beginning of this chapter. The connection scale tests presented in Chapter 4 are used to assess multiple drying environments and their effect on the mechanical properties of typical shear wall, sheathing to timber connections. Whole walls are then tested in Chapter 5 in order to verify the results of the connection tests and to investigate the effect flooding and drying has on failure mechanisms of shear walls. The results of the experiments performed at two different structural scales are used together in order to develop a better overall understanding of the behaviour of shear walls that have been flooded and restored by drying. This data provides experimental evidence to produce better drying and repair guidance for platform timber frame structures. The effect of flooding on the behaviour of timber shear walls is better understood by experimentation and new insights into potential failure modes are found.

In Chapter 4, multiple drying environments are studied. The investigation varies temperature and relative humidity. As such, the Taguchi method is used to plan and analyse the results. The specifics of the method are discussed in detail in Appendix A. The use of the Taguchi method allows the relative influence of the two environmental variables, temperature and relative humidity, to be studied. The effect of each variable on the drying of the specimens can be isolated and an overall optimum determined.

3.3 Assumptions

This study focuses only on the structural performance of timber shear walls. Although floor diaphragms are important in timber structures, transferring loads to the walls of the structure, it is the walls that come into direct contact with flooding. The shear wall and its connection to the foundations is responsible for resisting the imposed horizontal and vertical loads applied to a structure. This study is therefore restricted to understanding the behaviour of just walls in response to flooding. This approach is also has the advantage of being somewhat simpler experimentally, requiring construction of walls only, not a full structure.

This approach also allows advantage to be taken of existing test standards.

In Chapter 2, Section 2.7, it was argued that when drying, at least for timber structures, the time taken to dry is less important than recovering maximum mechanical properties. For timber buildings, the incorrect removal of excess moisture can degrade their mechanical properties, which could potentially compromise their structural integrity. As such, during the experiments conducted for this thesis, time taken to dry is not used as the criterion for "successful" drying. Instead performance is measured via recovery of mechanical properties. When drying, a "safe" value of timber moisture content is specified; $\leq 20\%$. This is the value at which timber can be considered safe from mould and rot due to excess moisture, see Chapter 2, Section 2.5.1. The MC will continue to vary naturally to reach EMC however, $\leq 20\%$ is a reasonable objective for assisted drying. All test specimens are therefore monitored for moisture content and when the target MC is reached, they are deemed ready for load testing.

3.3.1 Moisture content measurement

Throughout the experiments, moisture content is measured using a hand held, resistance type moisture content meter. In Chapter 2, different methods of estimating moisture content were discussed. The most practical of these is the resistance type moisture meter. It allows rapid assessment of moisture content in a minimally invasive manner and does not require any additional development to implement.

It is a much faster method than the gravimetric method which can take many days to produce a result although the MC meter is less accurate. A preliminary study at the beginning of the project excluded novel approaches to moisture content measurement such as NMR and electrical arrays.

For the test conducted in this thesis, moisture content will be estimated using a commercially available resistance type moisture content meter. It was chosen as it is easily available and commonly used to assess moisture contents. As noted in Chapter 2, the measuring accuracy of resistance MC meters is $\pm$ 2 - $\pm$5 % and the MC can very throughout the same piece of timber. Its use here replicates a likely post flood scenario in which non-timber-experts will be assessing timber frame.

3.4 Common experimental details

Full details of specific experimental set ups and procedures are given at the beginning of each Chapter where relevant. The following section contains details common to all experiments conducted during this project.

3.4.1 Materials

As mentioned in Section 3.2, the same materials are used throughout the project for each experiment. The 9 mm OSB/3 sheeting used is the minimum prescribed by design guidelines and is widely used in the house building industry [105]. It was chosen as it closely reflects the most common platform timber frame construction in the UK.

The choice of timber was made in an attempt to reduce experimental variability. A mixture of timbers is used in the UK [105] with European whitewood (a mix of silver fir and Norway spruce) in common use. With respect to European whitewood, it was not possible to find a supplier able to guarantee the exact species of each shipment. Douglas Fir was chosen as it is commonly used in the US and has been used in the UK [106]. The timber supplier was able to guarantee the species and provide the exact requirements specified, including kiln drying to $< 20\%$ MC and sawing to size before delivery.

Quarter sawn timbers were selected as they tend to distort less when selling. The material tests discussed in Chapter 2, Section 2.6.1, indicate that the OSB sheathing is the main cause for concern when timber frame structures are exposed to flood. OSB suffers permanent reductions in mechanical properties when flooded and dried. In contrast, the timber that comprises the frame appears to return to its pre-flood strength after drying. Based on the literature, the critical component in a shear wall is the OSB sheathing. This fact is also noted by a small number of guidance documents [83, 84] Using quarter sawn timber helps to

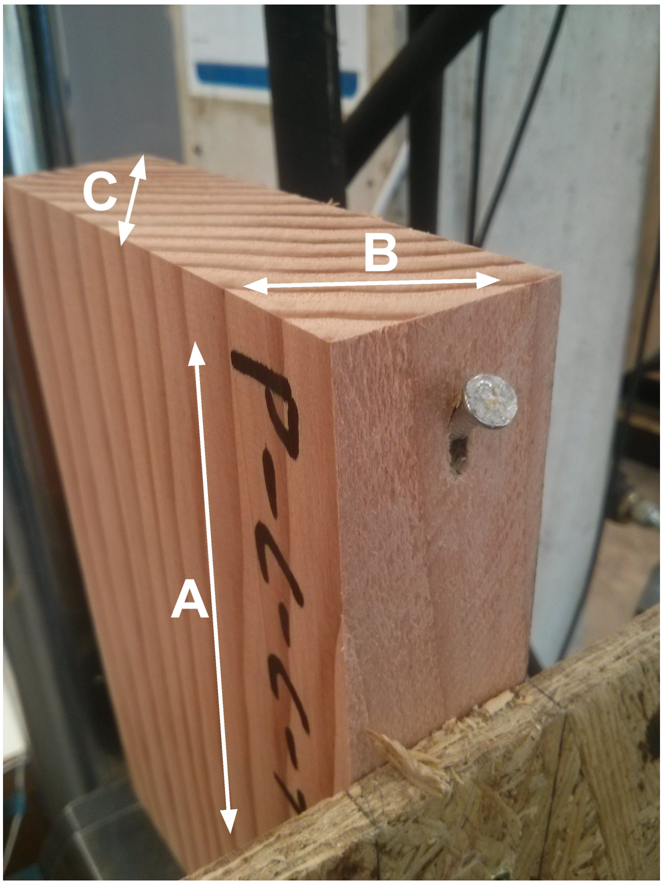


Figure 3-1: Grain directions in quartersawn timber. A) Longitudinal, B) Tangential and C) Radial. Specimens are loaded perpendicular or parallel to the longitudinal (A) grain. The example shown here is a specimen tested parallel to the grain.

limit the amount of uncontrolled variation in the timber, swelling and shrinking, during testing.

Quarter sawn timber is produced by cutting the timber perpendicular to the timbers radial face. This produces boards where the longitudinal grain of the timber runs along the length of the board, see Figure 3-1. As a result, two grain orientations will be tested in the work presented in the following chapters. Specimens will be tested either parallel or perpendicular to the longitudinal grain of the timber.

3.4.2 Flooding

The specimens tested in Chapter 4 are fully immersed in fresh water in a plastic tank for five days in order to simulate flooding. For the shear walls in Chapter 5, the University of Bath HIVE facility is used to flood the specimens. The specially constructed flood tank is closed using an aluminium barrier and filled with collected rainwater. The walls are flooded to a depth of 1 m. The depth of 1 m was chosen as it simulates a severe flood and allows an investigation into the behaviour of the walls when a significant portion of their height is flooded. Crucially a depth of 1 m is low enough that excessive uplift of the structure as described by Kelman and Spence [15] is not expected.

Chapter 4

Connection tests

4.1 Introduction

In this Chapter, the results of a series of single fastener connection tests are presented. These tests were designed to assess to what extent the mechanical properties of the sheathing to timber connections of shear walls are affected by flooding and subsequent drying and, to assess whether an optimum drying strategy can be determined. In order to assess multiple changes to the drying variables of temperature and relative humidity, Design of Experiment (DoE) techniques, specifically the Taguchi method, are used.

In Chapter 2, the relationship that the connection between the sheathing board and timber frame has on the behaviour of shear walls was introduced. It was seen that the connection often governs the behaviour of the entire wall. This behaviour is utilised by Källsner and Girhammar in their work, using connection strength to predict the failure strength of shear walls [46]. Studying the nailed connection between sheathing and timber therefore has the potential to generate useful data from which the general behaviour of a shear wall can be inferred.

In order to determine whether drying condition affects the mechanical properties of shear walls after flooding, a number of drying conditions must be investigated. Rather than attempt to implement every specific drying method discussed in PAS 64 [68] it was decided instead to investigate a range of temperatures and humidities. Each method of drying after flood discussed in PAS 64 works by controlling either temperature, relative humidity or both variables. Therefore, rather than attempting to use every different type of drying equipment; dehumidifiers, heaters, direct air mats etc…or combinations of these systems, a different approach is taken. Instead of using all possible equipment, the approach taken is one in which set drying environments are generated inside a climate chamber in which temperature and relative humidity can be controlled and maintained. This approach allows the use of equipment specifically designed to accurately control environmental variables. The application of the results back to a real structure then simply requires the choice of a drying system that can generate and maintain the environments investigated here. This approach will allow the tuning of specific drying systems to the data generated, rather than producing results that state one particular system is better than another. This method will identify optimum drying conditions, not the best drying technology.

The main area of interest in a flooded structure is the section below the flood water level. It is this area below the waterline that will suffer the majority of damage and subsequent potential loss of mechanical properties due to flooding. As the connection is often the critical component in a shear wall, testing of connections allows characterisation of the effects of flooding and drying on a typical point of shear wall failure. The choice to test connections is also influenced by practicality. Connections are far simpler, smaller and easier to produce and handle than whole walls. The specimens studied here were less than 500 mm in length, allowing them to be soaked, dried and tested within a normal Engineering laboratory. As seen in the following chapters, testing full sized walls requires the use of specialised equipment.

The literature review in Chapter 2 showed that there has been very little work investigating the effect of flooding and drying on timber frame. Previous work presented by the author at the World Conference of Timber Engineers in 2014 (WCTE 2014), showed that drying environment does affect the recovery of mechanical properties in connections [67]. The study concluded that a balanced environment with slightly elevated temperature and lowered relative humidity produced the greatest return to pre-flood mechanical properties. The environments investigated however, included extremes such as temperatures of 105 ^{0}C. These extreme conditions caused drying damage in the connections, as is to be expected. Furthermore, the drying environments were not chosen in a systematic manner and did not represent the range of drying environments likely to be utilised in a real flood restoration situation. The work presented here is based on the WCTE paper but investigates more reasonable ranges of temperature and humidity within bounds that are achievable with normal drying equipment. Parts of this chapter have been published as a peer reviewed paper in *Proceedings of the Institution of Civil Engineers, Construction Materials* [13].

4.2 The Taguchi method

In order to study more than one variable change at once and to separate out the relative effects of each variable, Design of Experiment techniques were used; specifically the Taguchi Method. A brief description of the method is given in the following section, for further information please see [107, 108] and [109] or Appendix A. The Taguchi method, developed by Genichi Taguchi [108] is a form of Design of Experiment (DoE) technique intended to optimise the efficiency and output of industrial processes such as manufacturing. The method is widely applied outside industry and allows the study of the effects of multiple parameters using a limited number of experiments. The approach has other advantages such as allowing the optimum process conditions to be determined during laboratory experimentation [110]. The basic approach to conducting an experiment using the Taguchi method is given by Barrado et al. [111] and is as follows:

1. Select the output variable to optimise
2. Identify *factors* and assign *levels*
3. Select the correct orthogonal array
4. Assign factors to columns of the array
5. Perform the experiments
6. Carry out statistical analysis of the data and determine optimum factor levels

7. Conduct a confirmation experiment

Here, *factors* represent input variables and *levels* are the values they take. The Taguchi method allows multiple experimental variables to be studied at once whilst reducing the number of experimental runs required. The method also allows the relative effect of the different variables to be identified. For example, the effect on a vehicle's fuel efficiency of three different suspension types, two tyre types and two fuel mixes could be determined without performing every combination of experiments. It would also be possible to determine which factor was the most influential on the overall outcome. A full description of the method is given in Appendix A. In this chapter, the method is used to separate the influence of the environmental variables of temperature and relative humidity.

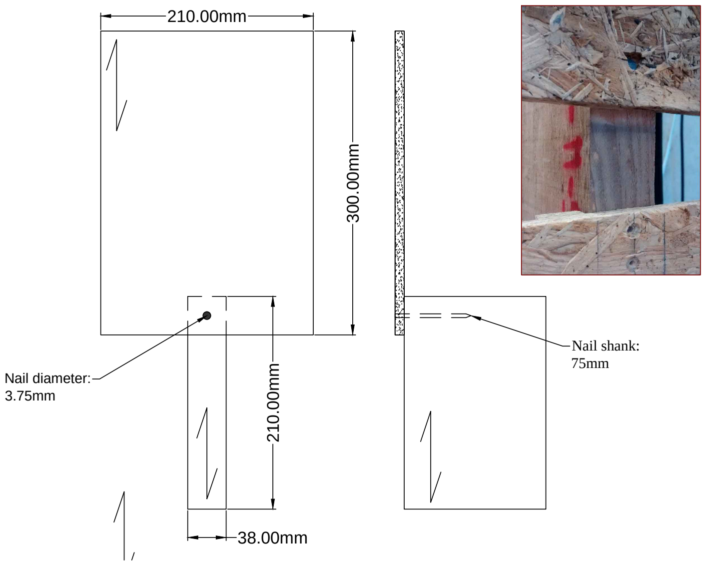
4.3 Experimental method

Experimental details specific to this chapter are given in the following section.

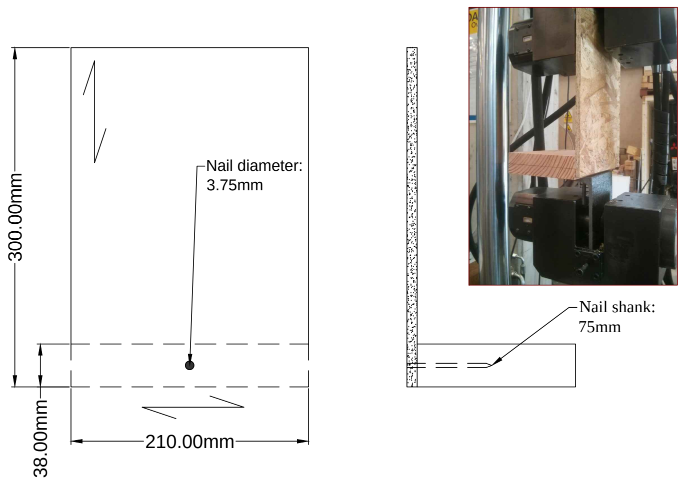
4.3.1 Specimen design and preparation

A series of tests specimens were constructed using quarter sawn Douglas fir sourced from a local saw mill, with 9 mm Norboard OSB/3 sheathing nailed to the timber using 3.75 mm diameter, smooth shank galvanized nails as prescribed by [39]. The timbers were 210 mm in length with a 38 mm $\times$ 140 mm cross section, with a mean dry density, $\overline{\rho} = 601$ kg/m^3 and an adjusted 5$^{\text{th}}$ percentile adjusted dry density of $\rho_{05} = 592$ kg/m^3 [112].

The OSB/3 sheathing was 210 mm $\times$ 300 mm and fixed to the timber by a single nail hand-driven into a pre-drilled hole. Holes were pre-drilled such that the diameter $\leq 0.8\ \Phi_{\text{nail}}$ as per Eurocode 5 [53]. The OSB/3 was located on the timber as shown in Figure 4-1 such that the edge distance between the nail and the sheathing sheet reflected the edge distance found in a typical shear wall where 38 mm $\times$ 140 mm timber studs are used. This gives an edge distance of 19 mm. Specimens were constructed with two different grain orientations such that they are loaded either parallel or perpendicular to the longitudinal grain (see Figures



(a) design of specimen loaded parallel to grain.



(b) Design of specimen loaded perpendicular to grain.

Figure 4-1: Connection specimen assembly diagrams. Figure 4-1a is the specimen loaded parallel to grain and Figure 4-1b is the specimen loaded perpendicular to grain. The two headed arrows indicated the longitudinal grain direction of the timber. It is this grain direction that the specimens are tested relative to.

4-1a and 4-1b) in order to allow any effects that grain orientation may have on the properties of the connections to be investigated. OSB grain direction is not studied as Vessby et al. [113] have shown that it is not an influential factor in such tests.

Specimens were placed in a plastic tank and fully immersed in fresh mains water for 5 days before being removed and dried under one of the conditions in Table 4.1. Three specimens of both grain orientations were dried in each of the specified drying environments. In addition, three specimens of both grain orientations were tested without wetting and drying in order to act as control specimens. All test results are compared against the control specimens. These control results are assumed to be equivalent to the original strength of specimens before any wetting or drying occurred. A total of 60 specimens were tested; 6 control specimens and 54 exposed variously to the nine different drying conditions. The connections tested are similar to those studied by [114] and [115]. The studies by [114] and [115] investigated the effect of edge distances and the effect of different board types on the connection strength. Here however, the testing is only concerned with the effects of wetting and drying therefore, the edge distances are kept constant and only OSB is investigated.

4.3.2 Drying environments

As mentioned in Section 4.1, the study in [67] investigated a broad range of drying climates, some of which were outside the range of likely drying environments. For the study presented in this chapter, a range of drying conditions were chosen that are considered more realistic than those investigated in the preliminary study in [67]. The chosen drying conditions are presented in Table 4.1.

Table 4.1: Drying environment variables studied during the connection tests. Combinations of all temperature and humidity variables were investigated.

Temperature (^{0}C)	Relative Humidity (%)
18	20
30	40
38	80

The temperature levels are kept below the limit of 41 ^{0}C suggested in [64]. Relative humidity is investigated at three levels. The levels are chosen to represent typical outdoor humidities, 80%, the optimum level suggested by Garvin et al. [66] (see Table 2.3) and a humidity level deliberately lower than the suggested optimum. The lower level was chosen in order to determine whether:

a) low humidity conditions caused a measurable effect on the system and,

b) the effect caused was significant in terms of reduction in mechanical properties.

Each combination of temperature and humidity was investigated for drying efficacy. In order to account for multiple changes to two variables, Design of Experiment (DoE) techniques were utilised, specifically Taguchi methods [108]. This approach is explained in detailed in Appendix A. In this series of experiments, a full factor array is used so no experimental runs are saved however, the analysis techniques of the Taguchi method are used to help understand the relative influence of the temperature and relative humidity on drying efficacy.

Orthogonal array for connection tests

The drying environments to be assessed are given in Table 4.1. There are two factors studied, Temperature (T) and Relative Humidity (RH). Each of these factors can take one of three levels. The levels can therefore be assigned to the orthogonal array given in Table 4.2. This approach allows the relative influence of each factor to be studied. The EMC given in Table 4.2 is the moisture content that each specimen is expected to reach if it were to be left in the drying environment until it reached equilibrium.

The effect of flooding on a number of different mechanical properties will be assessed, therefore there are multiple output variables to consider for this experiment. The results for each output variable are analysed independently as discussed in Section 4.2. To investigate the influence of grain direction, the experiment is run twice. Experiments 1-9 (Table 4.2) are performed independently for each grain orientation.

Table 4.2: The orthogonal array for the connection test experiments. This array gives nine experimental runs. Values in parenthesis are factor level numbers. Factors are referred to by an abbreviation, with the number representing the level. T2, for example, is temperature at level 2 and RH3 represents relative humidity at level 3. The EMC is the moisture content that would be expected to be reached if the specimens were left in the drying conditions. Values according to [62].

Experiment Number	Temperature (^{0}C)	Relative Humidity (%)	EMC (%)
1	20 (1)	20 (1)	5
2	20 (1)	40 (2)	8
3	20 (1)	80 (3)	16
4	30 (2)	20 (1)	4
5	30 (2)	40 (2)	8
6	30 (2)	80 (3)	16
7	38 (3)	20 (1)	4
8	38 (3)	40 (2)	7
9	38 (3)	80 (3)	16

4.3.3 Drying

In order to dry the specimens at each of the different conditions, an environmental chamber was used. The chamber used was a plant growth room capable of maintaining internal conditions within the required limits. The chamber produced a turbulent airflow of 0.2 m/s and is capable of up to 4 air changes per hour. Specimens were placed on wire racks within the chamber to ensure equal exposure to the drying environment on all drying surfaces, see Figure 4-2. The exposure to the drying environment on all surfaces of the specimen means that the drying boundary conditions are not the same as would be expected in a real life setting. As such, time taken to dry is not measured as this would be inaccurate due to the boundary conditions.

As discussed in Chapter 2, Section 2.7, in a real structure the drying process is controlled from the inside of a room and the structure is exposed to two different drying environments; one on the internal face that faces into a room and one on the external face that faces the cavity gap, see Figure 2-13. In the drying chamber the entire specimen is exposed to the drying environment, thus it will dry at a different rate to a wall in a real structure. Although the effect of the

Figure 4-2: Specimens drying in the environmental chamber. Each specimen is arranged to provide maximum airflow around it, ensuring equal exposure to the chamber conditions and even drying of each specimen.

drying environment is the same as would be experienced in a real structure, the time to dry is not.

4.3.4 Moisture content

As discussed in Chapter 2, the MC of the specimens is monitored using a two pin, resistance type moisture meter. Uninsulated pins were inserted 4 mm into both the sheathing and timber parts of the specimens. MC was therefore taken as a near-surface reading in each specimen. This method of MC monitoring is the least invasive and allows determination of the moisture levels without unduly affecting the strength of the specimen through removal of material. Although holes could be drilled in order to facilitate depth profiling of moisture content, due to the small size of the specimens, the loss of material could unduly influence their mechanical performance. In addition, the absolute MC of the specimen is less important than simply knowing the specimen has dried sufficiently. The critical point for property owners and those contracted to dry after flood is knowing when the frame has dried sufficiently.

The MC meter used is capable of reading between 6% and 43% MC. Values above 43% are recorded as +44%. The moisture level of specimens was recorded before wetting, after 5 days of wetting and periodically during the drying process. When a MC of $\leq$ 20% was achieved, the specimens were deemed to be sufficiently dry and were load tested. A final measurement of MC was taken prior to loading.

4.3.5 Load testing

Specimens were were loaded monotonically under displacement control at a rate of 2 mm/min in a universal testing frame. Displacement control is chosen over load control as it provides more accurate command of the loading process. The loading set up is illustrated in Figures 4-3 and 4-4. Loading was continued until specimen failure. For all specimens the OSB sheathing was clamped in place by the upper jaws of the testing frame. For specimens loaded parallel to grain, the timber was held by a second sheet of OSB board fixed to the specimen with screws. The board was then clamped by the lower jaws of the testing frame, Figure 4-3. For the specimens loaded perpendicular to grain, an angle bracket was bolted to the specimen through the timber, then clamped by the lower jaws of the test frame, Figure 4-4. Preliminary tests showed these methods of fixing to be adequate; no displacement was observed at the connection between the loading frame and specimen. The only displacement occurred where expected; at the location of the nail fixing the OSB to the timber. Displacement (mm) and force (kN) were recorded using the on board sensors of the test frame. The accuracy of the on-board sensors was verified using an external transducer and load cell. The force displacement data was used to derive the mechanical properties; ultimate strength, yield strength and initial stiffness. An example load slip curve is given in Figure 4-5. Definitions of the mechanical properties are given in Section 4.4.

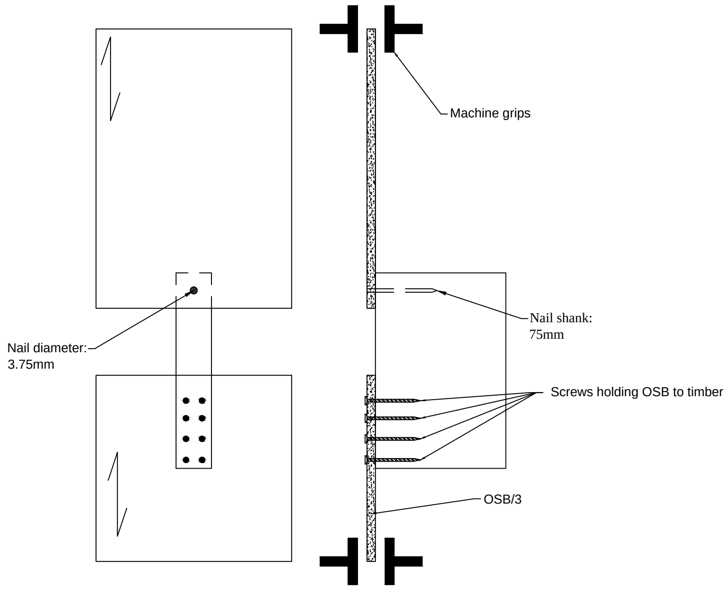


Figure 4-3: Loading set-up for the parallel to grain specimens. The OSB sheathing is clamped by the upper jaws. The lower jaws hold the secondary OSB that is fixed to the specimen with a minimum of 4 screws. This set-up ensures displacement only occurs in the nailed connection.

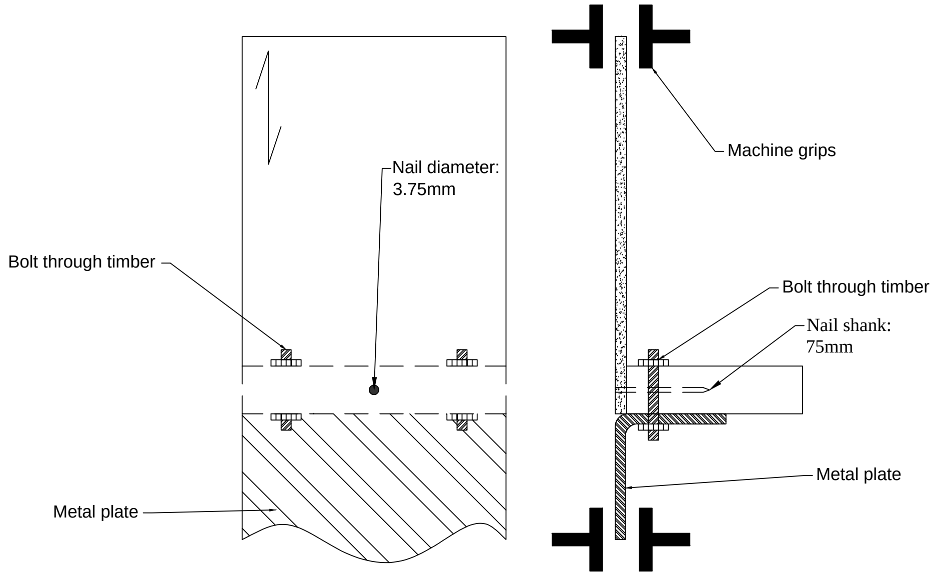


Figure 4-4: Loading set-up for the perpendicular specimens. The OSB sheathing is clamped by the upper jaws. A metal plate is bolted through the timber and held by the lower jaws. Bolts are tightened until the washer begins to bear on the timber. This set-up ensures displacement only occurs in the nailed connection.

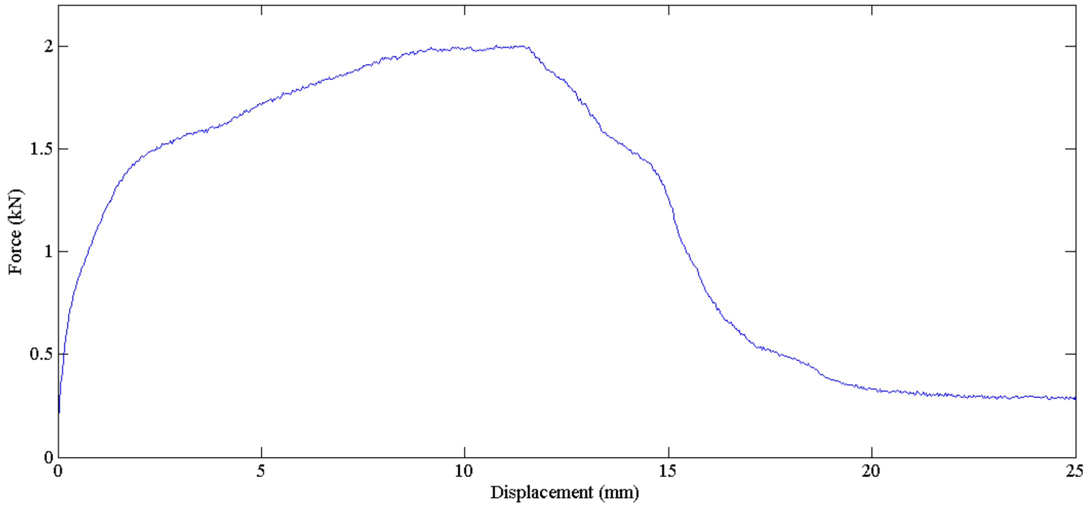


Figure 4-5: Example load slip data for connection tests on a control specimen. The yielding and failure of the specimen can be clearly seen.

4.4 Results

The results of the the connection tests including visual observations and derived mechanical properties are presented in this section.

4.4.1 Moisture content

Moisture content was measured before and after wetting and prior to load testing.

Table 4.3: Values of moisture content measured during the testing process for all specimens. The OSB MC was always greater than the scale of the moisture meter after soaking for five days. Values in parenthesis are standard deviations.

	Moisture Content (%)
OSB $_{\text{initial}}$	11 (1.2)
OSB $_{\text{wetted 5 days}}$	44+ (N/A)
OSB $_{\text{test}}$	15 (3.4)
Timber $_{\text{initial}}$	15 (0.8)
Timber $_{\text{wetted 5 days}}$	36 (1.7)
Timber $_{\text{test}}$	13 (3.5)

The OSB MC at five days of wetting was checked against a number of individual OSB specimens that were cut from the same sheet and soaked for the same length of time. These specimens were found to have a mean MC of approximately 80% as determined by the oven dry method [57]. In some cases moisture contents of over 100% were observed. Comparison of the moisture contents in Table 4.3 shows that the OSB is clearly far more susceptible to water absorption than the timber. It is also worth noting that the MC's for both OSB and timber are significantly above the FSP, placing them at increased risk of mould and decay.

The criteria for "sufficiently dry" used in this study is simply a moisture content of $\leq 20\%$. This choice of moisture content level is informed by Chapter 2. Whenever the MC was observed to be below the threshold in both elements of connections, specimens were load tested. This results in greater variation in the MC at testing compared to MC prior to testing as drying rates differed slightly between specimens.

4.4.2 Ultimate strength

Ultimate strength, F_u, is defined as the maximum load experienced by the specimen during loading. The results for each experiment and grain orientation are given in Table 4.4. Values in parenthesis are the Coefficient of Variation (%), for each test. The Coefficient of Variation (CoV) is the ratio of the sample standard deviation to the sample mean, expressed as a percentage:

$$\text{CoV} = \frac{\sigma}{\mu} \times 100 \tag{4.1}$$

Table 4.4: Connection test results for ultimate strength. The results for each grain orientation do not show a statistically significant difference at α=0.05. The data are therefore combined to generate the value of F_u given in Column 3. Values in parenthesis are coefficients of variation expressed as percentages.

Experiment Number	$F_{u,parallel}$ (kN)	$F_{u,tangential}$ (kN)	$F_{u,combined}$ (kN)
1	1.28 (29)	0.87 (12)	1.07 (31)
2	1.00 (43)	1.12 (38)	1.06 (37)
3	1.00 (18)	0.69 (25)	0.84 (27)
4	1.01 (21)	1.15 (26)	1.16 (33)
5	1.07 (35)	1.68 (23)	1.38 (34)
6	0.95 (40)	1.19 (49)	1.07 (43)
7	1.16 (09)	1.53 (23)	1.35 (23)
8	1.24 (19)	1.38 (35)	1.31 (27)
9	1.06 (18)	0.95 (14)	1.01 (16)
Control	1.64 (18)	2.14 (30)	1.86 (27)

A t-test at α=0.05 shows that there is no significant difference between the mean values of F_u for parallel and tangential specimens at each drying condition. This signifies that grain direction of the timber has no effect on the ultimate strength of the specimen. In this case, the results for each grain orientation can be combined, as shown in the third column of Table 4.4. The results shown in column three are used to generate the response chart in Figure 4-6. From Figure 4-6, it can be seen that a combination of temperature at level 3, T3 = 38 ^{0}C, and relative humidity at level 2, RH2 = 40% RH (experiment number 8), account for the greatest

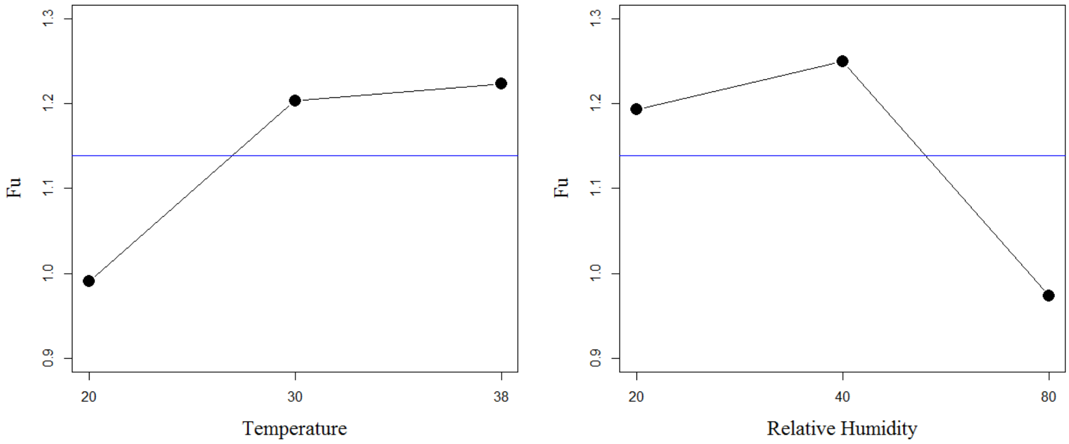


Figure 4-6: Response plot for combined ultimate strengths of connections. The horizontal line is the mean value of F_u for all experiments; $\overline{F_u}$ = 1.14 kN. The left hand chart shows the effect temperature has relative to the mean and the right hand chart shows the effect of relative humidity on the mean. Optimum conditions are at T3, RH2.

increase in F_u compared to the mean strength of all tests combined. The mean strength of all tested specimens, $\overline{F_u}$, is 1.14 kN. The value of $\overline{F_u}$ is 61% of the value of F_u for the control specimens. The predicted value of F_u at the optimised conditions, as found by taking a mean of the values at T3 and RH2, is 1.33 kN or approximately 72% of the control connection strength. On average specimens have lost 40% of their strength compared to the control specimens. This can be improved to a 30% loss of the original strength through correct drying.

4.4.3 Yield strength

The yield strength of the specimen is defined according to BS EN 12512 [116]. It is taken as the intersection of straight line extensions of the initial and plastic sections of the load slip curve. The value of force at the intersection point is taken as the yield strength, F_y. The results of a t-test at α=0.05 indicate that there is no grain dependency in the results obtained for F_y, the same as observed in Section 4.4.2 for F_u. Table 4.5 shows the mean yield strength for each grain orientation for each drying condition, as well as the combined data.

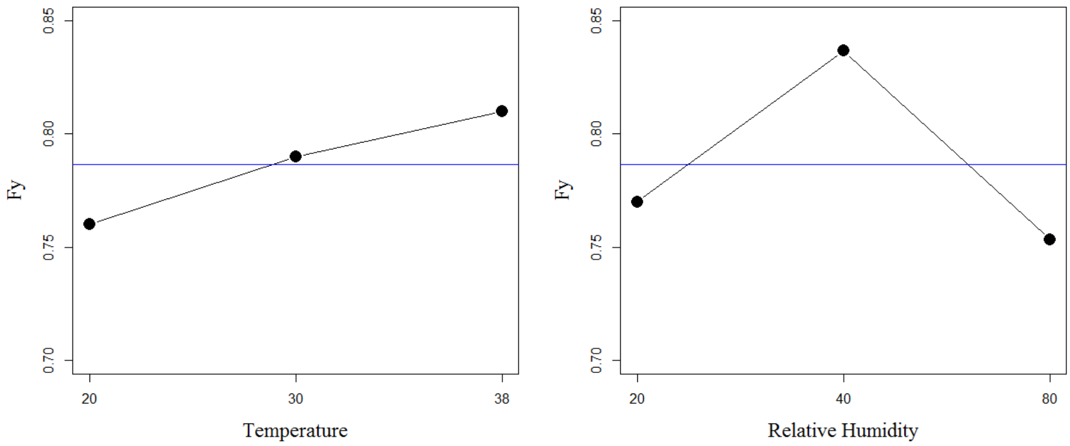


Figure 4-7: Response plot for combined ultimate strengths of connections. The horizontal line is the mean of all experiments, where $\overline{F_y} = 0.79$ kN. The left hand chart shows the effect temperature has relative to the mean and the right hand chart shows the effect of relative humidity on the mean. Optimised factor settings are the same as for F_u; T3, RH2.

Table 4.5: Connection test results for yield strength. The results for each grain orientation do not show a statistically significant difference at α=0.05. The data are therefore combined to generate the value of F_y given in Column 3. Values in parenthesis are coefficients of variation expressed as percentages.

Experiment Number	$F_{y,parallel}$ (kN)	$F_{y,tangential}$ (kN)	$F_{y,combined}$ (kN)
1	0.80 (23)	0.63 (06)	0.82 (29)
2	0.71 (10)	0.74 (34)	0.77 (26)
3	0.70 (09)	0.58 (33)	0.69 (29)
4	0.62 (26)	0.72 (029)	0.75 (28)
5	0.73 (05)	0.92 (21)	0.81 (21)
6	0.62 (26)	0.99 (36)	0.81 (40)
7	0.73 (06)	0.76 (33)	0.74 (22)
8	0.87 (20)	0.98 (13)	0.93 (16)
9	0.84 (12)	0.68 (03)	0.76 (14)
Control	1.22 (16)	1.35 (12)	1.28 (14)

The combined data are plotted on a response chart showing the influence of temperature and relative humidity in Figure 4-7. Figure 4-7 indicates that the optimal condition for maximising F_y is the same as for F_u; temperature at 38 ^{0}C and relative humidity at 40%. For yield strength, the mean value for all tested specimens is $\overline{F_y} = 0.79$ kN or 61% of the control specimen F_y. The optimised factor settings predict a yield strength of 0.86 kN or 67% of the control value. Drying conditions again influence the specimen strengths and correct drying improves the recovered yield strength by 6%. Although improved, the effect is not as significant as for F_u.

4.4.4 Stiffness

Stiffness, k, is the initial stiffness of the load slip curve. It is defined as the secant stiffness between $0.1F_u$ and $0.4F_u$ [116]. Statistical testing shows that there is

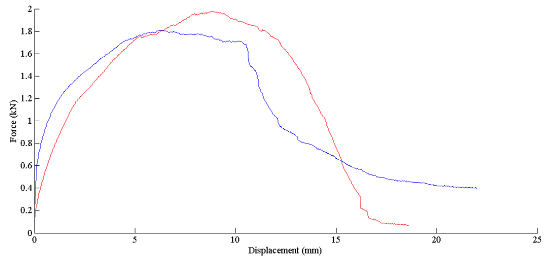
Table 4.6: Initial connection stiffness for both parallel, k_p, and tangential, k_t, grain directions. Tangential stiffness, k_t, is generally greater than k_p.

Condition	k_p (kN/mm)	CoV (%)	k_t (kN/mm)	CoV (%)
1	0.64	25.2	0.69	35.7
2	0.72	01.4	1.87	20.6
3	1.11	19.5	1.72	24.8
4	0.57	12.8	2.44	32.1
5	0.40	24.2	3.63	33.7
6	0.78	17.9	3.89	25.9
7	0.43	08.4	2.66	29.4
8	0.76	07.4	6.53	18.3
9	0.59	28.0	0.50	22.0
Control	1.09	44.4	4.79	52.2

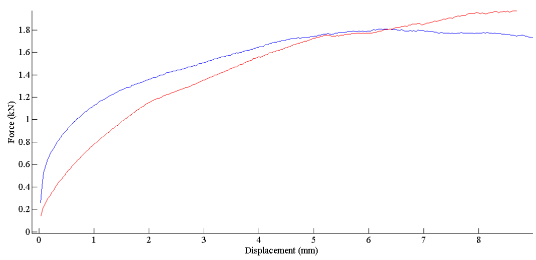
a significant difference between the mean values of k for each grain orientation. This is evidenced by the fact that for the majority of experimental runs, stiffness is greater in the tangential to grain direction, k_t, compared to the parallel to grain direction, k_p. There is also a large amount of variation in the stiffness values. In some cases the coefficient of variation is as high as 52%.

This high variation is clearly illustrated in Figure 4-8, where load slip data for two tangential specimens from experiment 5 are shown. The stiffness of the two specimens are 4.90 kN/mm and 2.46 kN/mm. One is approximately twice as stiff as the other, despite the fact both specimens were prepared, dried and tested in the same way. This large difference in stiffness is due to the natural variation in the timber.

The stiffness results presented here are unusual. It might be expected that the parallel to grain specimens are stiffer than the tangential to grain specimens however, in this case the opposite is generally true. This behaviour is discussed in Section 4.5.2.



(a) Entire load slip curve of two condition 5 tangential specimens.



(b) Initial section of the load slip curve of two condition 5 tangential specimens.

Figure 4-8: Comparison of the load slip curve for two “condition five” specimens. Fig. 4-8a shows the entire load slip curve and Fig. 4-8b shows the initial loading section from which the stiffness is derived. Note the difference in stiffness despite the same preparation, drying and loading regimes for all specimens. Initial stiffness for the two specimens are 2.46 kN/mm and 4.90 kN/mm. This variation is due to the natural variability of the timber.

4.4.5 Visual observations and failure modes

A number of important visual observations were made during the testing program and are detailed here. Following the five-day soaking process, significant thickness swelling of the OSB board was observed. The swelling due to wetting was always between 11-12 mm or approximately 22-33% of the original thickness original thickness was 9 mm. In Chapter 2, the expected swelling o OSB after 24hrs immersion in water was given as 15% according to [90]. Here, the observed swelling is 5-10% greater.

Swelling was often un-recovered by drying. The swelling resulted in splitting of the OSB board as the adhesive between laminate layers ruptured due to the swelling forces (Figure 4-9a) caused by the timber fibres that make up the OSB expanding as they absorbed water. This is the mechanism reported in [81] that leads to a permanent loss of strength. The swelling also resulted in the nail head either punching through the board or a "dishing" of the board around the nail head, Fig. 4-9b. The severity of adhesive rupture varied, with some specimens showing large gaps between laminate layers and others very little. The variation is due to the local fibre structure of each board at the location of the nail.

(a) Example of swelling in the OSB sheathing.

(b) Example of the nail head punching through OSB due to thickness swelling of OSB.

Figure 4-9: Examples of OSB swelling causing splitting between laminate layers, Fig. 4-9a and the punching of the nail through the sheathing board due to thickness swelling, Fig. 4-9b. In Fig. 4-9a some of the gaps are > 1.5 mm wide.

Observed failure modes were consistent across all tests. Only two, related failure modes were observed during testing; nail rip-out or nail pull through. Nail pull through refers to the nail head pulling out from the back of the OSB board, Figure 4-11b. Rip-out refers to the nail tearing through the base of the sheathing board, Fig. 4-11a. These modes are consistent with those reported in [47] for hardboard sheathing and those reported for OSB by [113] and [42]. The manner in which the nail rips out of the sheathing varies. In some cases a clean rip is observed, with the nail cutting a clean groove through to the base of the board, Fig. 4-11c. In these cases the OSB fibres break along the nail displacement trajectory. In other cases the entire fibre length appears to be pulled through the sheet, resulting in far more displaced material, Fig. 4-11d. Inspection of the specimen after loading revealed that the nail had undergone bending within the timber, Figure 4-10. This bending was localised to the external edge of the timber. The radius of bending decreased along the length of embedded nail. Importantly, none of the specimens inspected showed any sign of nail displacement along its length; there was no evidence of nail withdrawal from the timber. This suggests that the pull out force on the nail due to the OSB swelling was not sufficient to displace the nail axially. The punching of the nail head through the OSB occurs because the OSB embeddment strength is reduced by wetting.

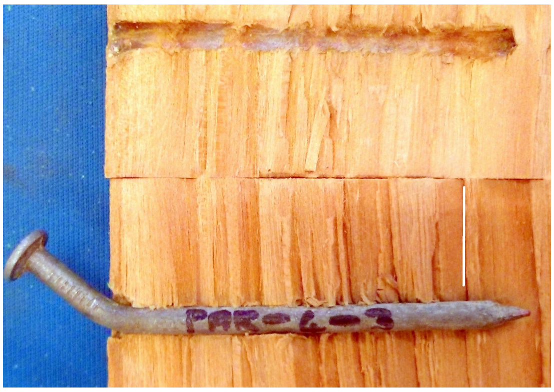


Figure 4-10: Specimen opened after testing to show degree of nail bend. There is no axial displacement and only limited bearing into the timber at the open end of the nail hole. The nail bend is approximately 40^0. This specimen was tested parallel to grain. Grain direction indicated by white line.

In a small number of specimens, five of the sixty tested, it was found that the contact surface between the OSB and the timber was still visibly wet, Figure 4-12. This is despite the fact that measurements had suggested that the specimens were at a MC of $\leq 20\%$. The area that was found to be wet is inaccessible without the destructive disassembly of the specimen. It is therefore likely that a similar phenomenon of hidden areas of elevated MC could occur in a real structure that has been subject to flooding. This phenomenon is important to be aware of when surveying flooded timber structures and highlights the importance of correct MC survey techniques. The method of depth profiling discussed in PAS64 [68] and Chapter 2 whereby material is removed to allow access for insulated pins should be followed to ensure the structure is definitely sufficiently dry. The specimens

(a) Nail ripped out of OSB base.

(b) Nail pull through back of the OSB.

(c) Clean nail rip out of the OSB base.

(d) Nail rip out of OSB base showing increased displaced material.

Figure 4-11: Different failure modes of OSB sheathing in connection tests. The difference between nail rip-through and pull out is shown in Figures 4-11a and 4-11b. The variation in displaced material and damage to the sheathing when the nail rips out the base is illustrated by Figures 4-11c and 4-11d. These failure modes are consistent with those observed in [42] and [113].

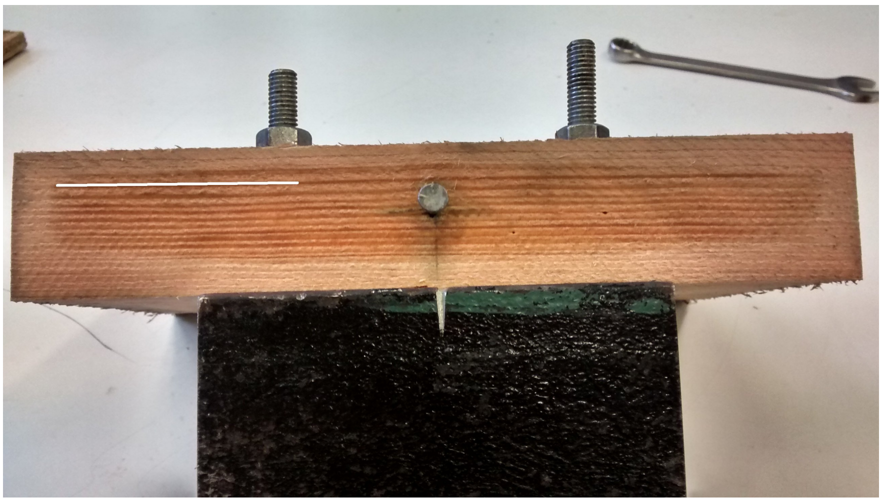


Figure 4-12: Trapped moisture concealed inside a tested connection. This area of elevated moisture content could not be seen until after specimen disassembly. Note also the bolts and metal plate for fixing the specimen to the loading frame as detailed in Fig. 4-4. This specimen was tested perpendicular to grain. Grain direction indicated by white line.

where these wet patches were observed were dried at 38^0C and 80% RH. This illustrates the importance of lowering RH to achieve effective drying. As noted in [58], [64] and [117], RH must be lowered for drying to occur. An environment with a high RH limits the effectiveness of drying as there is insufficient gradient for rapid moisture evaporation from the timber into the environment. Simply elevating temperature alone will not improve the effectiveness of drying.

4.4.6 Confirmation experiment

As stated in Section 4.2, an important step in the Taguchi method is performing a so called "confirmation experiment". The confirmation experiment is run in order to confirm the experimental conditions that were determined as optimum are indeed optimum. Another set of 10 specimens were constructed, wetted and then dried at the optimum condition of 38 ^{0}C and 40% RH. Only parallel specimens (see Fig. 4-1a) were tested as it had already been determined that strength was not grain dependent. The OSB governs the strength and this is independent of grain direction [113]. The mean mechanical properties of the confirmation connection tests are given in Table 4.7.

Table 4.7: Mechanical properties derived from the connection confirmation tests at the optimum drying conditions. These results are compared to the original experimental run and the predicted results. Values in parenthesis are coefficints of variation.

	F_u (kN)	F_y (kN)
Confirmation test	1.25 (22)	0.84 (17)
Original Experimental run	1.31 (27)	0.93 (16)
Predicted values	1.33 (/)	0.86 (/)

Wet connection test

At the same time as performing the confirmation tests for the optimum condition, a further 10 specimens were load tested immediately after wetting for five days. Again, as for the confirmation tests, only parallel specimens were tested. This data allows the connection performance when wet to be observed. The results are presented in Table 4.8

Table 4.8: Results of the wet connection tests. Mechanical properties F_u and F_y are given. Values in parenthesis are coefficients of variation expressed as percentages.

	F_u (kN)	F_y (kN)
Wet connection	1.04 (35)	0.67 (31)

The mean ultimate strength, F_u, of the wet connections is 56% of the control specimen ultimate strength. F_y is 52% of the control yield strength. When wet, the connection suffers a significant reduction in mechanical properties. Figure 4-13 shows the load slip curve for all specimens tested. The variation in the data is clearly visible. For 10 specimens fabricated from the same timber (in this case, the same plank) and the same OSB board, a significant variation between specimen behaviour can be observed, see Fig. 4-13.

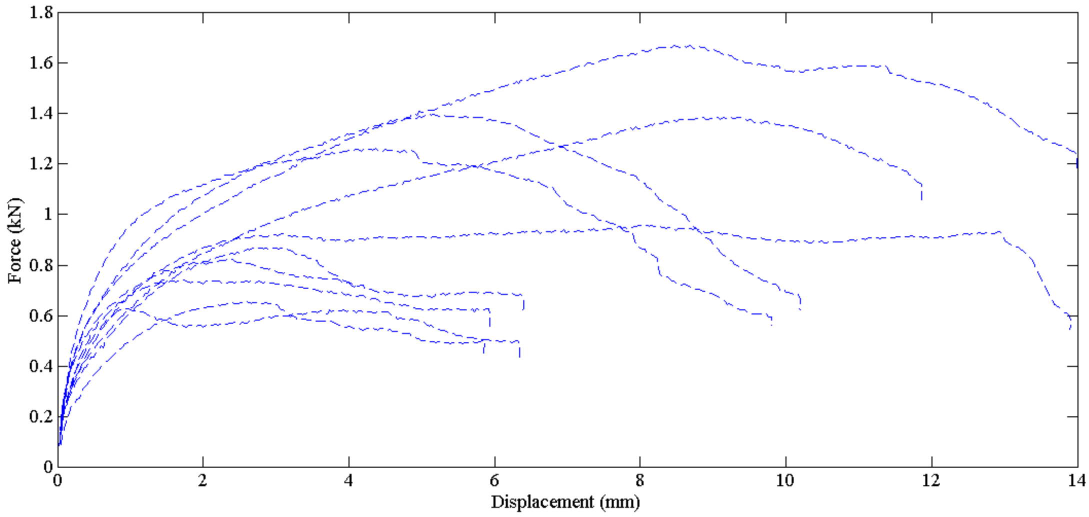


Figure 4-13: Load slip curves for the wet connections tested. Significant variation between the behaviour of individual specimens can be observed. For wet specimens, strength and slip vary greatly.

4.5 Discussion

4.5.1 Strength comparisons

Results for the connection mechanical properties, ultimate and yield strength, F_u and F_y, were given in Sections 4.4.2 and 4.4.3. These data show that there is clearly a loss of both F_u and F_y in all connections as a result of the wetting and drying process. For F_u, the overall mean connection strength was 1.14 kN. This is an approximate reduction of 40% compared to the control specimen strength. For F_y this value was 0.79 kN or again, a reduction of approximately 40% compared to the control specimens. Changing the drying environments altered the percentage of control strength recovered. For F_u, increasing the temperature at which specimens were dried resulted in the value of F_u increasing, see Fig. 4-6. The improvement is not however, linear;

A change in temperature from 20 ^{0}C to 30 ^{0}C results in a far greater increase to F_u than a change of 30 ^{0}C to 38 ^{0}C. Similarly, a reduction in RH tends to improve the value of F_u. Reducing the RH always improves the recovered strength when compared to the strength at RH = 80%. There is a reduction in F_u from 40% RH to 20% RH although it is limited to just 0.06 kN. The value of F_u for specimens dried at 20% RH is still greater than for those dried at 80% RH. The slight decrease in strength when dried at 20% RH could be drying damage as a result of the specimen drying too quickly at an excessively low relative humidity.

It can also be seen from Figure 4-6 that the influence of RH is greater than that of temperature. Variation in temperature accounts for a range of 0.23 kN, or 20% of the mean value of F_u whereas the range of means for RH is 0.28 kN, or 25% of the mean value of F_u.

The predicted value of F_u at the optimum factor levels is 1.33 kN or 71.5% of the value of F_u for control specimens. In order to optimise strengths, the specimens should be dried at a temperature of 38 ^{0}C and a relative humidity of 40% as this result sin the greatest return to strength with respect to the pre-flood state. For yield strength, the same is true. From Figure 4-7 it can be seen that raising the temperature results in an increase to the value of F_y and reducing the humidity from 80% also increases the value of F_y. For relative humidity a reduction from

40% to 20% decreases yield strength although, drying at 20% or 40% RH both result in greater strength recovery than when dried at 80% RH. The yield strength is significantly less influenced by changing of factor levels. Changing factor levels results in a range of F_y of 0.05 kN and 0.08 kN for temperature and relative humidity respectively. Although the drying can be optimised for yield strength it has far less effect than for ultimate strength. The optimised factor settings predict a yield strength of 0.86 kN or 67% of the control value.

Summary

These results show that there is a permanent reduction in connection strength as a result of wetting and, this reduction varies depending on the drying environment used. None of the drying environments studied resulted in a full recovery of strength. A permanent loss is always to be expected. The choice of drying environment does therefore affect the strength of the specimen. Altering the temperature and humidity at which the specimen is dried will affect how much strength can be recovered. Optimising drying for strength requires a temperature of 38 ^{0}C and 40% relative humidity. The recovery of strength will generally improve as the temperature increases and relative humidity decreases although not to the same degree as if the optimised drying conditions are used. When drying, if optimised settings cannot be achieved then it is suggested to increase the temperature and decrease the relative humidity. Given the relative influence the two factors have on recovered strength, if only one can be controlled it is best to control the RH as it has greater influence over the recovered strength.

4.5.2 Stiffness

As mentioned previously in Section 4.4.4, the results for the connection stiffness are unusual. It might be expected that perpendicular to grain specimens would be less stiff than the parallel to grain however, in this case the opposite is true. The parallel to grain specimens are, in general, less stiff than the perpendicular.

This behaviour is likely to be due to the fact that the connection specimens are fixed with nails. Due to their small diameter, the nails in the nailed connection can “slip” between the fibres of the timber when loaded parallel to the grain. In the perpendicular (tangential) to grain specimens, the nails are loaded across the fibres, compressing the fibres. This leads to the behaviour where the parallel specimens exhibit lower stiffness than the perpendicular as previously seen in Vessby et al. [113].

Previous work on timber connections also shows either large ranges of stiffness or large variations in stiffness [42, 118, 119]. In some cases, very large variations of more than 50% CoV in timber connection stiffness are reported [120]. The large natural variability of timber properties is well known [56], and it is this variability than causes such a wide range range of stiffness in the connections tested both here and in previous works. The high degree of variability seen in these results can be attributed to the fact that the stiffness is dependent on a single localised section of timber and is therefore subject to, and a function of, the natural variation of the timber itself.

Similar work

In 2014, Vessby et al. [113] presented results of similar connection tests at the World Conference on Timber Engineering. Their study investigated the effect of OSB and timber directionality on the connection behaviour. Two forms of tests were conducted;

1. Embedment test of nails into;
    a) OSB/3 in isolation and,
    b) Timber in isolation.
2. Load tests of the OSB and timber elements assembled as connections.

Vessby et al. [113] found that despite the orthotropic nature of the OSB, differences between the two perpendicular directions in which the OSB were loaded were limited. They conclude that the directionality of OSB can be discounted for such connections. They did however, find that the major differences in behaviour were as result of the timber orientation.

The authors found that specimens in which the timber was loaded perpendicular to the grain were stronger and stiffer than those loaded parallel to grain[1]. It can also be seen from their results that the load-slip curves have significant variation, especially for the longitudinal specimens tested. Although the authors do not publish figures for the stiffness (or variation) of the specimens, it is easy to infer the differences between specimens from the graphs provided. This behaviour is the same as observed in the tests presented in this chapter.

In their paper, Vessby et al. [113] do not attempt to deal with the unusual stiffness results. Stiffness is, in fact, not explicitly discussed at all.

Other factors

There are a number of compounding factors that must be considered when viewing these stiffness results. Firstly, neither the tests presented in this chapter, nor those conducted by Vessby et al. [113] attempt to measure the contribution of elastic strain in the OSB, a factor which may influence this effect.

Secondly, the tests presented in this chapter utilised two slightly different fixing methods. As such, there may be discrepancies between the two fixing methods and the results may in part be a reflection of the difference in system stiffness. This may account for some of the difference between the two grain orientations.

Conclusions

Although these results are an area of interesting discussion, stiffness of the connection specimens is not particularly important to this study. The stiffness data are a less useful predictor of wall behaviour than the strength data derived from the specimens. For example, whilst the study by Okabe et al. [44] found that connection strength was closely correlated to wall strength it found stiffness did not correlate so well. The reason for this is simple, a simple single-nailed connection has limited scope for generating stiffness; a single nail embedded in the

[1]The authors actually use Longitudinal and Tangential in their paper to mean parallel and perpendicular

timber. This element is highly dependent on variation in local material properties. A shear wall is a more complex system with more scope for generating stiffness such as framing joints and the shear stiffness of the OSB sheathing.

The connections are too simple to properly represent the behaviour of a full wall system with respect to stiffness and, due to local material variations, the results have a high CoV. Previous research has also shown the connections stiffness to be a less accurate predictor of wall stiffness than the connection strength. It is likely that a decrease in stiffness will be observed in full sized walls subjected to flooding. Changes in material properties and loosening of connections caused by swelling are possible mechanisms for this. It is however, unlikely that the losses will be identical to that observed in the connections that were tested.

4.5.3 Failure mechanism

In Sections 4.4.2 and 4.4.3, strength data for tangential and parallel specimens were combined. This was because statistical testing showed no significant difference in strength between the grain orientations. This indicates that the connection strength is not dependent on the grain orientation of the timber. Additionally, the visual observations made during testing (Section 4.4.5) show the failure of each specimen is always located in the OSB. There are no failure modes apart from nail rip out or pull through in the OSB sheathing; failure never occurs via nail withdrawal from the timber, failure of the nail or any other failure mode. As strength is independent of grain orientation of the timber stud and failure always occurs in the OSB sheathing, the strength of the connections must therefore be governed by the behaviour of the OSB. This is supported by the results presented by Vessby et al. [113]. Furthermore, the losses in connection strength were unrecoverable although the type of drying chosen affects the severity of strength loss. It is known from the work presented in Chapter 2, Section 2.6.1, that OSB suffers permanent damage due to wetting and that timber tends to regain its original strength. Connection strength is governed by the OSB therefore, damage to the OSB from flooding causes permanent losses in connection strength.

The tests are set up such that each connection is loaded so that the OSB moves relative to the timber. It is suggested that the initial displacement of the connection causes the nail to bear into the timber at the outer edge of the nail hole, see Figure 4-10. At this stage, the bearing pressure on the OSB is less than its bearing resistance. Continued displacement of the connection results in the bending of the nail. This bending causes more of the nail length to actively bear into the timber, increasing the area of timber resisting the bearing pressure. When this surface is sufficiently large, the bearing pressure of the nail and the bearing resistance of the timber reach equilibrium, preventing further bending of the nail. Relative displacement of the connection is still continuing, thus one of two things can happen;

1. Either the nail can withdraw from the timber or,
2. the OSB will begin to fail.

The withdrawal resistance of the nail in the timber is always greater than the axial force exerted on the nail by loading therefore, the OSB must begin to fail.

Continued loading causes OSB failure of the types shown in in Figure 4-11. The withdrawal capacity of the nail is a result of the axial friction along the length of the nail between the nail shank and the timber into which it is embedded. The utilisation of the withdrawal resistance is commonly referred to as rope effect. This behaviour is shown in Figure 4-10, where the nail bend and bearing into the timber can be seen. The image was captured after connection failure and it is clear that the nail has not withdrawn from the timber. The crushing of the timber around the end of the nail hole is visible.

The continued displacement of the OSB results in the nail shank in effect cutting a path through the sheathing. The nail does not however, cut this path cleanly as a saw would. Rather, as the OSB fails and material is ripped out, fibres are displaced within the sheet, Fig. 4-11. The displaced fibres may break relatively easily resulting in a cleaner line cut through the board, or may "bunch up" and displace within the sheet, resulting in compression of the sheathing around the nail bearing surface, increasing the thickness of the board in this area, Fig. 4-11b. If the resulting compression force is sufficiently high, the nail may pull through the back of the board rather than rip through the base of the OSB sheet.

This observed failure mode accounts for the lack of grain dependency in relation to F_u and F_y and the consistent specimen failure in the OSB. Ultimate failure of the specimen in the OSB is to be expected. Permanent reduction in the mechanical properties of OSB as a result of elevated moisture content is previously documented [80–82]. The loss of sheathing capacity is as a result of swelling in the fibres that make up the OSB. This swelling due to moisture absorption is sufficient to cause rupture of the adhesive that bonds the layers of the boards together. As shown in Table 4.3, the MC of the OSB increased on average by more than 33% and always increased to above the FSP. Given the MC increase and the observed swelling, it is reasonable to expect a reduction in board strength and therefore the overall strength of the tested specimens.

4.5.4 Confirmation tests

From Table 4.7 it can be seen that the results of the confirmation test are in good agreement with both the original experimental run and the predicted values. According to [107], a difference between the predicted results and confirmation results of an experiment of approximately ± 5% can be considered a good agreement. For F_u, the ratios of the original results and predicted results to the confirmation results are 1.048 and 1.064 respectively. Similarly, for F_y the ratios are 1.12 and 0.98. Ultimate strengths are closer to the original experimental values and the yield strengths are closer to the predicted values. Stiffness is not compared in the table as it is not possible to combine the stiffness values for the original tests into a single value. A single comparison can however be made between the confirmation test results and the condition 8 parallel stiffness results. Condition 8 is chosen as it is the same conditions as the optimum drying condition. The stiffness of the parallel specimens dried in condition 8 was 0.76 kN/mm, which compares favourably to the confirmation stiffness of 0.71 kN/mm. Thus the confirmation tests show that the original experimental data is an accurate predictor of the connection properties at the optimised drying condition.

Comparison of specimens from conditions 1-9 to the wet connection results indicates that, apart from for conditions 3 and 9, drying has improved the mean ultimate strength of the connection from its wet state. In the case of F_y, drying always improves the connection strength.

The loss in mechanical properties due to wetting is recovered by drying however, different drying conditions result in different strength recoveries. If the correct environment is used, the restored connection strength should be greater than when wet.

4.5.5 Overall optimisation

With regards to the overall optimisation of drying, F_u, and F_y require the same conditions to achieve optimal drying. As discussed in Section 4.5.2, the stiffness of the connection is less representative of wall stiffness compared with the connection strength and wall strength relationship, therefore, the stiffness is not considered.

Strength was found to be optimised at drying conditions T3, RH2 or 38 ^{0}C and 40% RH.

Considering just ultimate strength, a simple interpretation of Table 4.4 would suggest that the optimum drying environment is condition 5 as the condition 5 specimens had a measured average ultimate strength of 1.38 kN. This simple interpretation does not allow the individual influence of temperature and relative humidity to be observed. Ranking the specimens in order of strength does not reveal any obvious patterns to the data with respect to environmental variables. Further confounding this simple approach is the fact that the yield strength, F_y, does not rank in the same order as F_u, see Table 4.5. What can be inferred from the simple numerical ranking is that increasing temperature and decreasing relative humidity tends to improve the strength of the specimen. The Taguchi approach allows a more detailed examination of the influence of temperature and relative humidity on the mechanical properties. This approach has enabled an optimised drying solution with respect to strength to be determined.

It is proposed that a temperature of 38 ^{0}C and 40% RH be used as the global optimised drying environment. This environment optimises F_u and F_y. Although this environment is proposed as the most optimal, there are two practical considerations that are important to keep in mind:

1. The relative humidity has more influence on the drying and recovered mechanical properties than the temperature.

- This is in agreement with the EMC values in Table 4.2 where Temperature little influence over the EMC.

2. There is a general improvement in recovery of mechanical properties as temperature increases and relative humidity decreases.

These two considerations are important as they allow informed judgements on drying to be made. When drying a real structure, if a choice has to be made between controlling temperature or relative humidity, it is better to control RH as it has more influence on the recovery of mechanical properties. Furthermore, if it is not possible to achieve the optimum drying condition exactly, lowering the humidity and increasing the temperature will, in general, improve the recovery of the mechanical properties. This is illustrated by 4-6 where the decrease in temperature from 38 ^{0}C to 30 ^{0}C has little effect on the strength of the specimen. This is true so long as the temperature is not too high or the humidity too low as this can result in damage.

4.5.6 Existing model comparison

The experimental results are used in conjunction with the Källsner and Girhammar model to predict full sized shear wall strength. The Källsner and Girhammar model [46] predicts the ultimate strength of a shear wall based on the plastic connection capacity.

It is also possible to model the load slip curves of the connections using a modified version of the Foschi Load slip equation [121]. The modified equation, proposed by Girhammar et al. [115] more accurately represents the connection behaviour after failure. Modelling the connections in this fashion would allow "average" connection properties to be used as input for advanced models such as finite element models however, FEM is beyond the scope of this project so this approach is not taken here.

Källsner and Girhammar model

Källsner and Girhammar have produced a series of papers on the subject of modelling shear wall strength. Their plastic capacity model [46], is the theoretical basis of the UK design document, PD 6693-1 [41] and Eurocode 5 Method B [53], for shear wall design [35]. Källsner and Girhammar's model uses the plastic capacity of sheathing to timber connections to predict the ultimate strength of a shear wall. The plastic capacity of the connection is converted to a per unit length value and used to calculate the ultimate load that can be sustained in racking. In order to apply Källsner and Girhammar's model, moments are taken about the shear wall. Moment equilibrium is established with the sheathing to timber connection capacity (expressed as a per unit length) used to limit the wall capacity. The Källsner and Girhammar model assumes that all connections behave plastically. The specimens tested in this chapter behave plastically and have similar load slip curves to the specimens tested by Girhammar et al. [115] and Salenikovich [114].

The conversion from connection capacity to a per unit length plastic capacity is simple. The connection capacity is divided by the nail spacing for the sheathing to timber connection used in a wall. In this case, the nail spacing is taken from design guidance as 150 mm [39]. The plastic capacity per unit length is therefore given by:

$$f_p = \frac{F_u}{\text{Nail spacing}}$$

where nail spacing is in meters. Using the moment equilibrium equations given in Källsner and Girhammar [46], the plastic capacity of the wall is determined using f_p as the limiting capacity of the connections.

The predicted racking strengths for each drying condition are based on the average value for $\mathrm{F_u}$ determined from the tests and are given in Table 4.9. These predicted racking strengths can then be compared to real wall test data. Here, a standard test wall according to BS EN 594 [122] is modelled. The wall is 2.4 m × 2.4 m with a stud spacing of 600 mm, a perimeter nail spacing of 150 mm, with imposed load on each vertical stud of 5 kN.

Comparison with existing results is difficult as so little research into flooded

Table 4.9: Predicted wall racking strengths ($H_{predicted}$) for a 2.4 m $\times$ 2.4 m wall. Strengths are predicted using the connection data derived in this chapter. The ultimate racking strength, H, is predicted according to the model by Källsner and Girhammar [46].

Condition	F_u (kN)	f_p ($\frac{kN}{m}$)	$H_{predicted}$ (kN)	$\frac{H_{predicted}}{H_{predicted,control}}$
1	1.07	7.13	13.23	0.64
2	1.06	7.07	13.10	0.63
3	0.84	5.60	11.75	0.57
4	1.16	7.73	14.46	0.70
5	1.38	09.2	14.48	0.70
6	1.07	7.13	13.23	0.64
7	1.35	9.00	14.04	0.68
8	1.31	8.73	13.43	0.65
9	1.01	6.73	12.36	0.60
Control	1.86	12.4	20.66	1.00

timber wall performance exists. It is possible however, to make approximate comparisons between values for predicted racking strength, $H_{predicited}$, based on the control specimen data and existing results given by Källsner and Girhammar. Tests presented by Girhammar and Källsner [47] use different types of hardboard as sheathing material as well as a range of hold down forces, loading directions and anchorage types. The experimental setup is therefore not directly comparable to that modelled by the connection tests in this chapter however, approximate comparisons can be made for the control specimens.

According to Girhammar and Källsner [47], for a two panel wall with vertical loading of 6.46 kN on each stud, the mean measured racking strength was 21.9 kN. Four repeat experiments were performed but no data is given on the variation of ultimate strength. . The plastic connection capacity of the walls tested by Girhammar and Källsner [47] is calculated to be $f_p = 12.5$ kN. This value is back-calculated from actual wall data, not derived connection tests. It is therefore the exact plastic connection capacity required for a given racking strength. This predicted ultimate strength value is close to that calculated using the control specimen data; 20.66 kN, see Table 4.9

There is good agreement between the calculated theoretical ultimate racking strength of a a wall based on the control specimen connection capacity and the results of similar walls reported by Girhammar and Källsner [47]. There is also excellent agreement between the plastic connection capacity calculated for the control specimens and the value derived by Girhammar and Källsner [47]. Although the verification of the results is limited, it appears that, at least for for the control specimens, the values of $H_{predcited}$ are reasonable.

4.6 Conclusions

A range of drying environments were studied to investigate their effect on the mechanical properties of nailed timber connections. The results show that the drying conditions used affect the ultimate and yield strengths of the connection. There is a permanent loss of strength due to wetting and drying and strength is governed by the OSB. Strength is not grain direction dependent.

The type of drying affects the recovery of strength and it was found that the optimal condition for restoring specimens closest to their pre-wetting strength was a temperature of 38 ^{0}C and a relative humidity of 40%. These conditions will result in a predicted ultimate strength, F_u, of 1.33 kN or 71.5% of the control specimen ultimate strength. For the yield strength, F_y, the optimised conditions predict a strength of 0.86 kN or 67% of the control value.

Comparison of the the effect of temperature and relative humidity indicate that RH is more influential than temperature for maximising the return to pre-wetting mechanical properties. Thus, if only one of the two can be controlled, it is better to control relative humidity. In addition, if the exact conditions presented here as optimum cannot be achieved, in general, increasing temperature and decreasing RH will improve the post wetting mechanical properties of the connection.

Results have been modelled using the Källsner and Girhammar plastic model. The connection mechanical properties were used to ultimate racking strength of a hypothetical shear wall. Although verification is limited to the control specimens due to lack of previous research available for comparison, it appears as though the application of the connection specimen data allows accurate modelling of the shear wall. Whether this relationship is still evident with respect to wetted and restored walls remains to be tested.

The key findings of this chapter can be summarised as follows:

- Different drying environments affect the return to strength of wetted specimens.
- Reducing the relative humidity and increasing temperature is shown to be effective in maximising return to strength of specimens.
- The optimum drying environment was identified as a relative humidity of 40% and temperature of 38 ^{0}C.
- Relative humidity was shown to be more influential in drying and improving return to strength of specimens than temperature.
- OSB governed specimen strength and permanent losses were observed.
- Wet connections were significantly reduced in terms of mechanical performance.
- Trapped moisture in some specimens illustrates the importance of correct moisture surveying techniques and the importance of lowering the relative humidity.

The results presented in this chapter show that simulated flooding and drying of a nailed timber connection causes permanent reductions in the mechanical properties of the connection. This is in agreement with test data for individual component materials that make up the connection. Furthermore, it can be shown that the type of drying influences the recovery of the mechanical properties and can be optimised to ensure the maximum return to strength of the connection. Observations indicate that it is the OSB which is at most risk of flood damage and that connection failure is always attributable to the OSB sheathing. The exact relationship between loss of connection capacity and overall racking strength of a wall is not possible to determine from these results alone. The relationship between connection behaviour and wall behaviour requires tests on shear walls and is studied further in Chapter 5.

Chapter 5

Shear wall tests

5.1 Introduction

This chapter presents the results of a series of tests on shear walls that were subject to simulated flooding. The concept is similar to that of the tests in Chapter 4 except the investigation is conducted on the full wall system rather than an isolated component of the wall. The connections tests in Chapter 4 allow a simple characterisation of wall strength to be made but do not generate any data related to wall stiffness, load paths or possible failure mechanisms of a complete wall assembly. The tests in this chapter will allow the structural behaviour of the wall after flooding and drying to be fully assessed.

Three types of wall are investigated, control walls, walls subjected to simulated flooding for five days and finally, walls that have been flooded and then restored by drying. The restored walls tested here were dried in the drying environment previously identified as optimum in Chapter 4. That is, a temperature of 38 ^{0}C and 40% relative humidity. Walls are subject to slightly modified versions of standard racking tests and the results are used to generate values for the mechanical properties of the walls to allow comparison of each condition. The measured results are also compared to predicted results from current models.

As has already been shown, there is limited work assessing the impact of flooding on timber structures. These results are therefore an important contribution as they are one of the few systematic investigations into the effects of flooding on timber shear walls available. The findings have significant implications for best practise restoration of timber walls following flooding. Parts of this chapter have been accepted for publication in the Elsevier journal *Engineering Structures*, see [123].

5.2 Experimental method

Experimental details specific to this chapter are given in the following section.

5.2.1 Wall construction details

A series of nine identical shear walls were constructed from the same stock of locally grown Douglas fir used in Chapter 4. Each wall was constructed from a timber frame, cross section 140 mm × 38 mm, clad in 9 mm thick "Norboard" OSB/3 sheathing. The walls were 1.8 m in height and 2.4 m in width, with a total of five vertical studs located at 600 mm centres (See Figs. 5-3 and 5-4). Walls were fastened using a "Paslode IM360Ci" gas powered framing nailer, Fig. 5-1. The same Paslode branded, 90 mm smooth shank, Φ 3.1 mm galvanised steel nails, Fig 5-2, were used for fixing the frame and sheathing. According to the manufacture, nails had a characteristic yield moment, $M_{y,k}$, of 3979 Nmm and were driven to a depth whereby the nail head was flush with the OSB surface. Nail spacing for the sheathing to timber connections was 150 mm for perimeter nailing and 300 mm for the internal connections. In order to simulate partial anchorage conditions, walls were anchored using 75 mm smooth shank, Φ 4 mm galvanised steel nails, one located between each stud as per guidance in [39] and [51]. The walls were anchored to a wooden rail which was held in place by steel clamps attached to the laboratory strong floor to prevent it sliding or lifting. This simulates a fixed sole plate connection to a foundation in a timber frame construction. All anchor nails were hand driven through pre-drilled holes in the bottom rail.

Figure 5-1: Gas powered framing nailer.

Figure 5-2: 90 mm galvanised steel nails.

Figure 5-3: Timber frame during assembly.

Figure 5-4: Fully assembled wall.

5.2.2 Wall test conditions

The nine walls constructed were assigned to three different conditions, giving three walls per condition which are as follows:

- Control (condition 1)
- Wetted 5 days (condition 2)
- Restored (condition 3)

The control walls, condition 1, are unwetted and are used as a reference for the other wall types tested. The wetted walls, condition 2, were soaked in rainwater for 5 days at a depth of 1 m. The restored walls, condition 3, were soaked in an identical fashion to the condition 2 walls. They were then dried in the optimum drying environment identified in Chapter 4 of 38 ^{0}C and 40% relative humidity. These conditions are summarised in Table 5.1.

Table 5.1: Conditions for shear wall tests. The control walls are used as the reference for the other two conditions. Condition 2 simulates a wall in the flooded state. Condition 3 simulates a shear wall after restoration.

Condition	Length of wetting	Temperature (^{0}C)	Relative Humidity (%)
1	N/A	N/A	N/A
2	5 days	N/A	N/A
3	5 days	38	40

Comparison of condition 2 and 3 walls against the condition 1 walls allows changes in mechanical properties and structural behaviour of the walls due to flooding and then subsequent drying to be identified. The data for the performance of condition 1 walls is assumed to be the "original" performance of the other wall types before wetting and restoration have occurred.

Wall flooding

Soaking of the walls was performed at the University of Bath's HIVE facility. This purpose built research facility allows full size building components to be assessed for performance in real world environments. This project made use of the specially constructed flood cell at the HIVE, Fig. 5-5, which enables flooding of specimens up to 1.2 m in depth. The flood cell is 4200 mm wide $\times$ 2200 mm deep $\times$ 1200 mm tall and is filled using captured rain water. Contaminated water is not used due to the difficulty in handling it safely. The risk from contaminated water puts it beyond the scope of this project. Walls were flooded to a depth of 1 m, a severe flood, but one at which buoyant uplift of the structure will not become the dominant issue. A depth of 1 m was also chosen as this is the depth to which the specimens studied by Leichti et al. [100] were flooded.

Due to a small amount of leakage from the flood cell barrier during the testing programme, on occasions the water level dropped to approximately 825 mm overnight. This lost water was topped each day by technical staff at the HIVE site. Thus, the water level varied between approximately 825 mm and the intended level of 1000 mm (1 m).

5.2.3 Load testing

All prepared walls were subject to racking tests as per BS EN 594 [122]. The testing deviated from the standard with respect to the height of the walls, which were reduced to 1.8 m due to overhead restrictions in the drying chamber. The walls were loaded with five hydraulic rams bearing on top of each vertical stud and a horizontal ram bearing on the leading stud, but not the sheathing, see [122]. The vertical load jack over the leading stud was offset by 100 mm as stated in BS EN 594. Load was applied via two hydraulic hand pumps. One pump directly controlled the horizontal load jack and one pump controlled vertical loading. The horizontal load jack was attached directly to the laboratory wall. The pump controlling vertical load was split across the five loading jacks and load was maintained at 5 kN. Applied load was measured via load cells, one connected to the central vertical ram and one connected directly to the horizontal ram. Vertical load jacks had Teflon bridge bearings placed between them and the sample wall to allow sliding of the wall underneath. Displacement was recorded using linear variable displacement transducers (LVDTs) at locations in addition to those prescribed by BS EN 594, including double transducers along the trailing edge of each wall to enable the recording of OSB and Timber displacements in-

Figure 5-5: Wetting of walls at the University of Bath's HIVE facility. The flood barrier has been disassembled to allow specimen removal. The high water line can clearly be seen on the specimens in the tank.

dependently. Loading and displacement recording locations are shown in Figures 5-6 and 5-7. Loading was continued until the wall failed or a deflection limit of 75 mm was reached or loading could no longer be safely maintained. The displacement limit of 75 mm is a modification of the limit given in the standard [122]. For a wall 2.4 m in height, the standard limits the deflection to 100 mm therefore for a wall 1.8 m in height, $\frac{3}{4}$ the height given in the standard, a deflection limit of 75 mm is used.

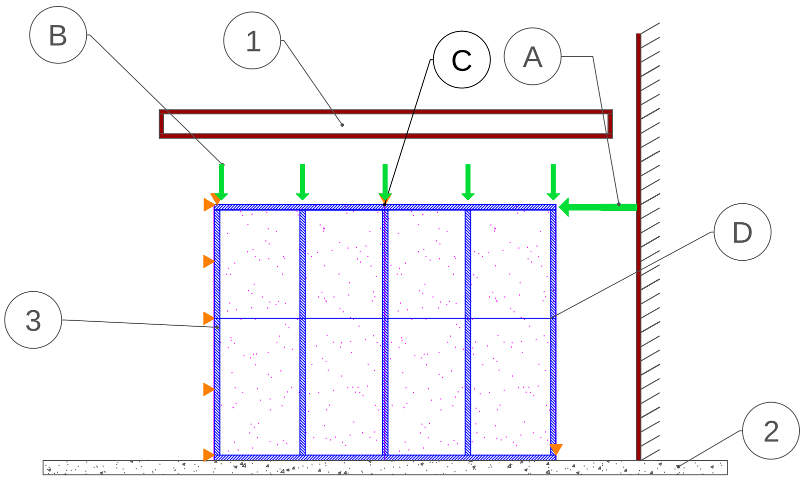


Figure 5-6: Diagrammatic representation of the loading tests. A) Horizontal force applied via dedicated loading jack and hand pump. Load monitored by a dedicated load cell. B) Vertical forces applied via five loading jacks controlled by a single hand pump. Load is monitored by a single load cell on the central load jack. C) LVDT locations represented by triangles. The trailing side of the wall was instrumented separately on the OSB and timber to allow independent measurement of displacements in the frame and sheathing. D) height of flood on wall, 1) steel frame to hold test equipment, 2) strong floor and 3) Shear wall.

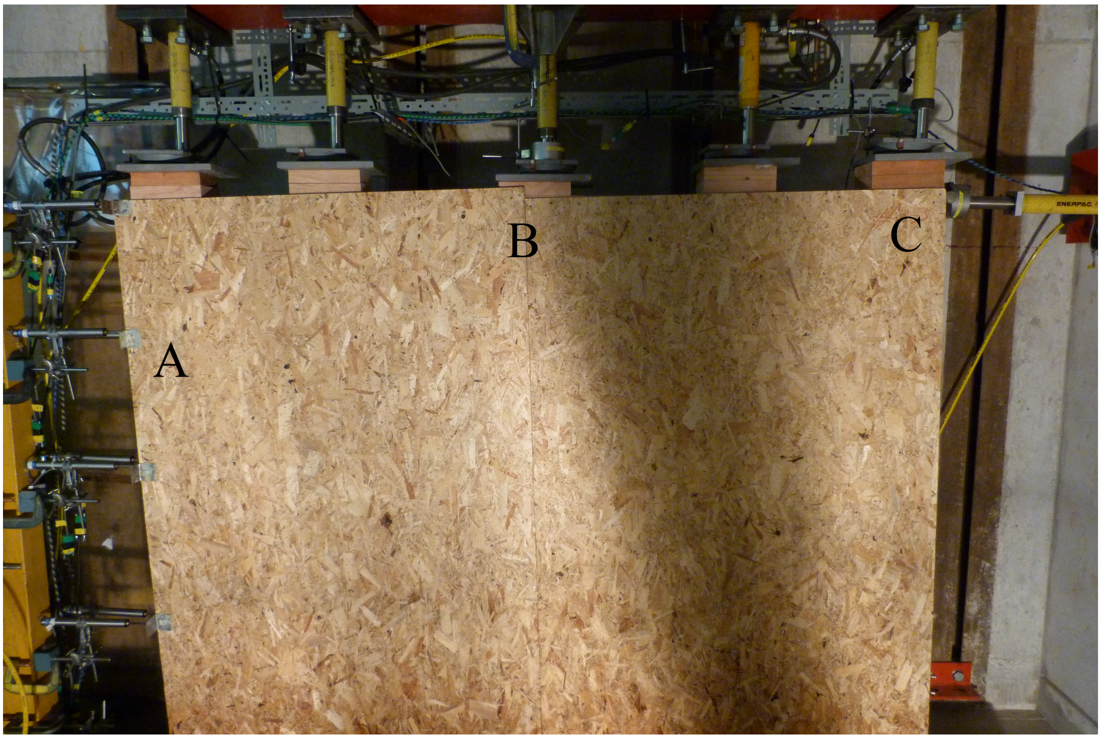


Figure 5-7: Wall during testing showing location of loading jacks and LVDT's. A) LVDT's monitoring the horizontal displacement of the OSB and timber. B) Vertical loading jacks and bridge bearings applying vertical loads of 5 kN per stud. C) Horizontal loading jack and load cell. This wall was under load when this image was captured, hence the visible displacement.

5.3 Results

5.3.1 Load slip data

Sliding of the wall on its foundations was monitored by transducers at the base of the trailing stud. Typical values of sliding were negligible; in the region of 0.004-0.02% of the displacement at F_{max}. This shows that the wall does not slide on its foundations by any significant amount during loading. The anchorage of the wall to the substrate, acting in conjunction with the imposed vertical load, is adequate. The wall is tested in racking and the eventual failure is due to other mechanisms, not sliding on the foundation.

Racking loads were applied using hand controlled hydraulic jacks. Testing using manual load control results in a somewhat erratic load slip data as manual load control is difficult to apply smoothly and evenly. With each stroke of the hand pump, the load will increase then fall off slightly. This effect can be seen in the raw load slip data in Figure 5-8. In order to smooth the data for analysis, envelopes through the data peaks were plotted as illustrated in Figure 5-8. This smoothed data enables simpler derivation of mechanical properties for each wall. The smoothed load slip curve for each condition are presented in Figure 5-9. For clarity the raw data have been omitted .

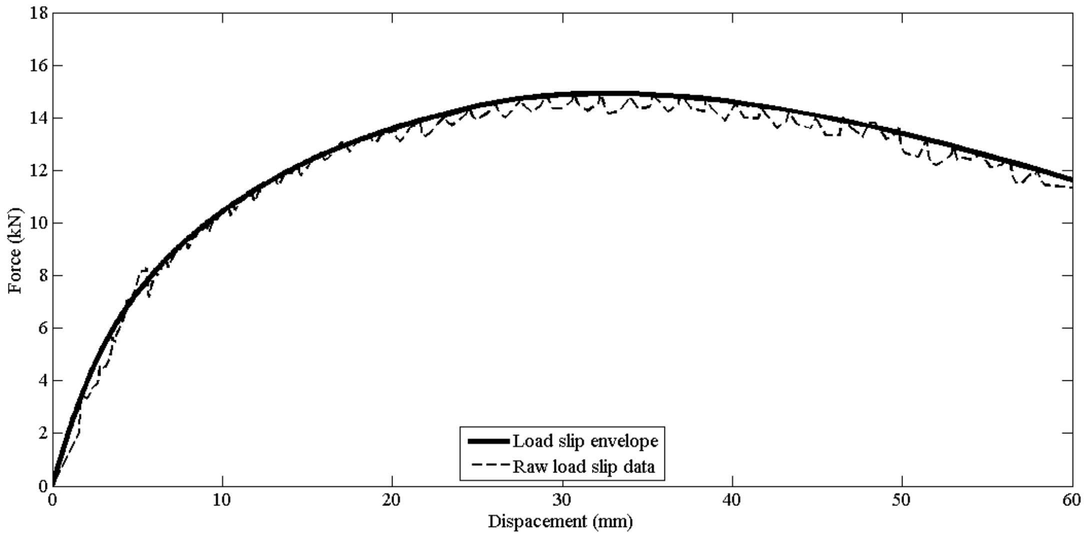
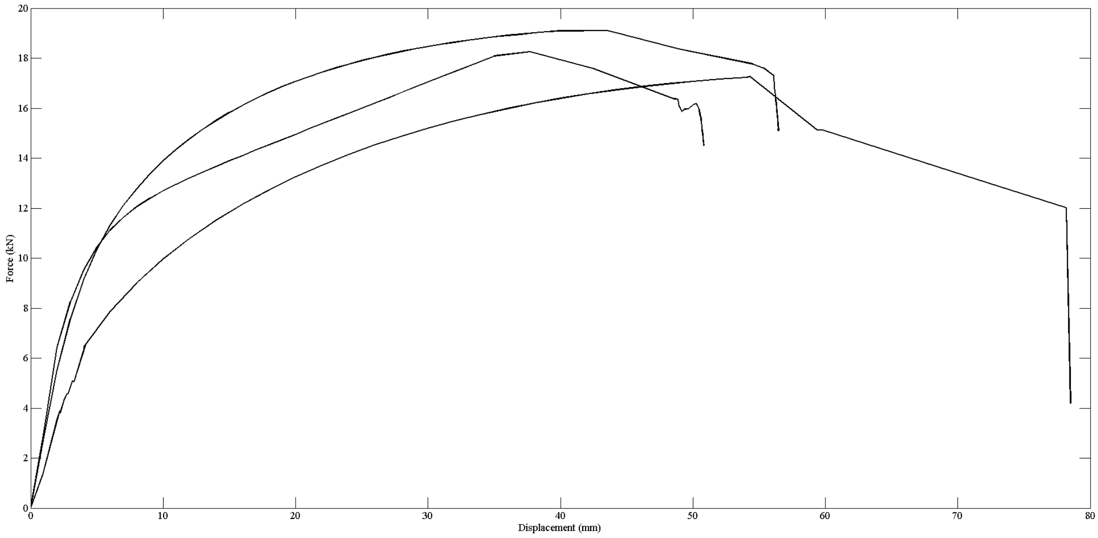
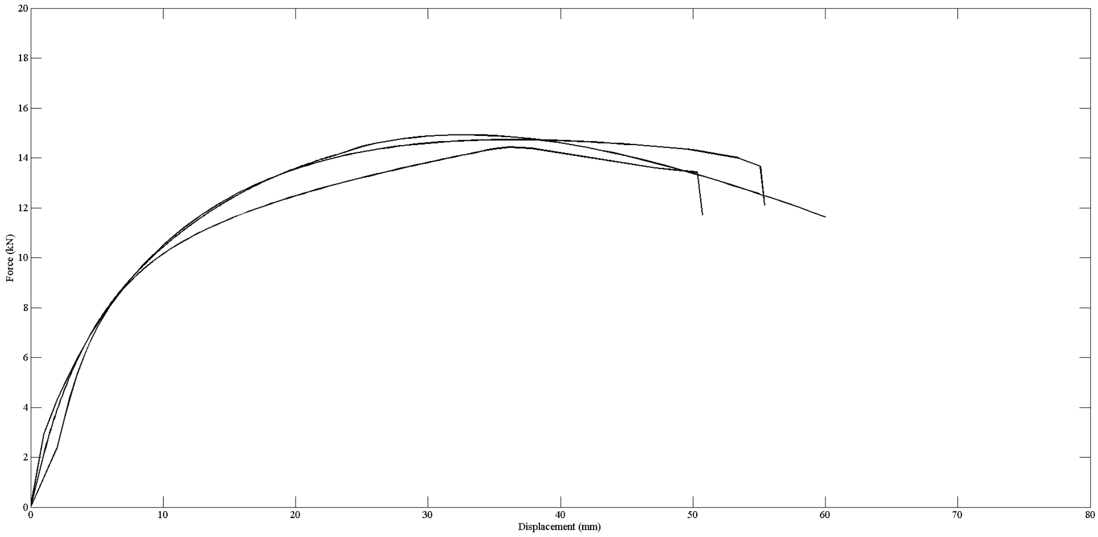


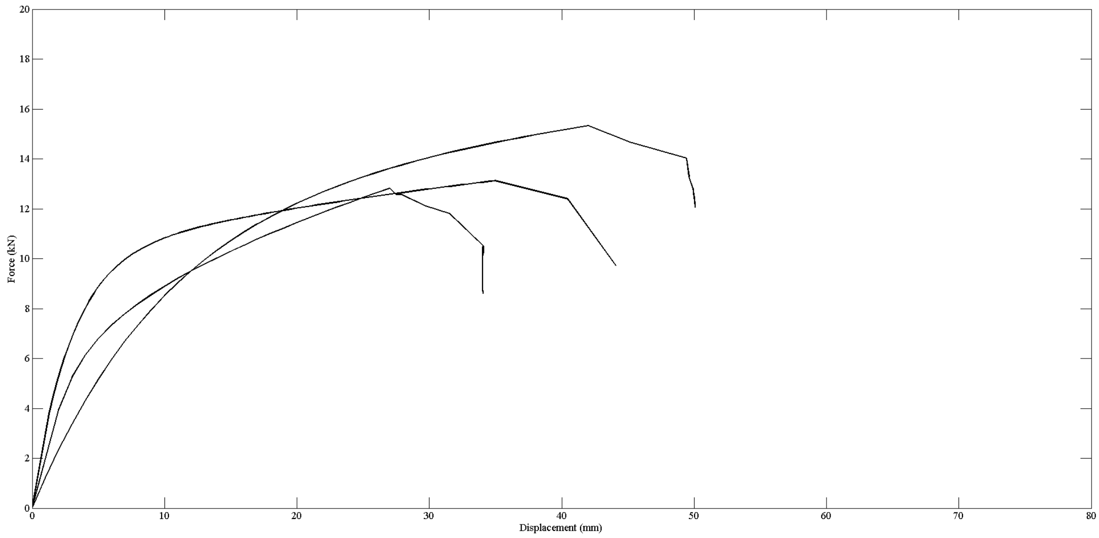
Figure 5-8: Example of envelope fitted to raw data to smooth out the effects of manual load control. A smoothed envelope is fitted through the data peaks. The increase in load and small decrease with each stroke of the hand jack can be seen in the raw load slip data.



(a) Applied load-displacement curves for condition 1 (Control) specimens.



(b) Applied load-displacement curves for condition 2 (Wet) specimens.



(c) Applied load-displacement curves for condition 3 (Restored) specimens.

Figure 5-9: Smoothed load load-displacement curves for all wall conditions tested. The curve is fitted through the raw data peaks as shown in Fig. 5-8. Fig. 5-9a are the results for the control walls, Fig. 5-9b are the results for the walls wetted for five days and Fig. 5-9c are the results of the restored walls.

5.3.2 Failure modes

During testing, the applied racking loads caused horizontal displacement of the wall. This resulted in differential displacement of the OSB sheathing and timber framing members, see Figure 5-10.

Wall failure was attributable to sheathing failure, with the nail tending to tear through the OSB sheathing where the differential displacement between the framing and sheathing is greatest. This failure progresses as the OSB continues to rotate relative to the timber framing members, see Figure 5-11. In some cases the nail was seen to pull out of the back of the OSB rather than rip through. These failure modes of the sheathing match those observed in Chapter 4 and those reported in [13]. At no point were nails observed to have pulled out of the timber, nor were they observed to have themselves failed.

Prior to testing it was noticed that the condition 2 and condition 3 walls exhibited severe warping of the sheathing board. This is caused by the OSB swelling when wet. Due to the OSB being restrained by the nail lines, the sheet buckles out of

Figure 5-10: Control wall illustrating typical failure of shear wall following load testing. The wall has displaced horizontally and the OSB sheathing has visibly rotated.

Figure 5-11: Progressive OSB failure of sheathing. Initial nail rip out occurs in the extreme corner of sheathing where relative displacement between timber and OSB is maximum. Failure then progresses to the nail at the location of next greatest relative displacement as overall wall displacement increases.

plane, rather than simply expanding. The out of plane buckling of the sheet is not recovered by drying. Generally out of plane behaviour is discounted in racking tests, however, out of plane behaviour is observed as a result of this warping in the OSB sheet. Figures 5-12 and 5-13 illustrate this warping. Note that in Figure 5-13, the warping is confined to the lower half of the wall where it was exposed to the flood. The upper section remains relatively undistorted.

This out of plane buckling occurred in the condition 3 specimens that already had curvature present in the sheathing. This failure due to out of plane bending is a result of the sheathing buckling off of the timber frame along a nail line. This is a failure mode to that is not expected nor accounted for in design codes. Examples of this failure are shown in Figures 5-14 and 5-15.

Figure 5-12: Horizontal curvature of the sheathing due to flooding. The OSB has a permanent out of plane curvature between studs. Note the gap between the edge of the level and the sheathing board due to the curvature.

Figure 5-13: Vertical curvature of sheathing due to flooding. The OSB has a permanent out of plane curvature between studs. The vertical curvature is less pronounced than the horizontal curvature in Figure 5-12. Note that the board distortion occurs only in the lower half of the wall where the OSB was wetted.

Figure 5-14: An example of the out of plane failure due to the bending of the sheathing. Here the curvature in the OSB has caused the sheathing to buckle away from the wall along the edge of a sheet.

Figure 5-15: Another example of the out of plane buckling failure due to the curvature of the sheathing. The sheathing buckles off the wall, with the nails pulling through the back of the OSB, rather than ripping out.

5.3.3 Ultimate strength

The ultimate strength, F_u, is defined as the peak load reached during testing. Table 5.3 gives the mean value of F_u for conditions 1 to 3. It can be seen that the control specimens have the highest mean value of F_u and that walls from condition 2 and condition 3 have reduced values of F_u in comparison. This demonstrates that the maximum load the wall can sustain is reduced when wetted as a result of flooding. Furthermore, it shows that there is a permanent loss in strength in the wall after restoration by drying. This is in agreement with results from the previous chapter and is expected based on the the results of individual material tests, see [63, 80, 81] and [82].

A one way ANOVA analysis was conducted to compare the means of the ultimate strength, F_u, of the shear walls tested under control, wet and restored conditions[1]. The ANOVA analysis indicated that there is a significant difference between the means; [F(2,6)=17.77, p = 0.003]. Post-hoc analysis via pairwise t-testing indicated that the control specimen mean was different from the wet and restored specimen means. The wet specimen mean F_u was not significantly different from the restored specimen F_u, see Table 5.2.

Table 5.2: Pairwise t-test comparison for shear wall ultimate strength, F_u. The wet and restored specimen means are not significantly different from one another. The t-test was single tailed, using the Holm p adjustment method.

Condition	p
Control - Wet	0.004
Control - Restored	0.002
Wet-Restored	0.860

Only the control specimen mean is significantly different to conditions 2 and 3, suggesting that drying has not enabled the wall to recover to a greater strength than it possessed when wetted. As shown in Table 5.3, both condition 2 and condition 3 walls show reduced displacement at ultimate load when compared to the control walls.

[1] Analysis was performed in the open source statistical package R.

Table 5.3: Mean values of ultimate strength, F_u, for shear walls tested. Conditions 2 and 3 are significantly weaker than 1, but not significantly different from each other. Condition 3 has the greatest variance in the the value of F_u and Δ_u.

Condition	F_u (kN)	CoV (%)	Δ_u (mm)	CoV (%)
Control	18.2	5	45	19
Wet	14.7	2	35	06
Restored	13.8	10	35	28

5.3.4 Yield strength

Yield in timber structures is difficult to define as in most timber structures "*...the load displacement relationship is non-linear and there is no distinct transition between the elastic and plastic behaviour...*" [124]. It is further stated in [124] that different analysis methods result in varying values for the yield deflection, Δ_y, of the system being tested, ultimately affecting the calculated ductility.

In determining the yield strength of the tested walls, a comparison of two models was made. It was decided to compare the results for yield produced by the Karacabeyli and Ceccotti model [125] (Figure 5-16a), hereafter referred to as the K&C model, and the Yasumura and Kawai model [126] (Figure 5-16b), hereafter referred to as the Y&K model. These models were chosen as they locate the yield point directly on the load slip curve.

This is in contrast to the European model given in [116], which defines yield displacement, Δ_y, as the displacement at the intersection of two lines defined on the load slip curve. The intersection of these lines is not necessarily on the raw load slip curve. In the European model, the first line used to define Δ_y is the initial stiffness between 0.1 and 0.4 F_{max}. The second line used to define Δ_y is one that lies tangent to the loading curve and has $\frac{1}{6}$ the gradient of the first. This approach does not necessarily locate Δ_y on the loading curve, thus potentially underestimating the true value of Δ_y. Another commonly used model, the Equivalent Energy Elastic-Plastic (EEEP) Curve, consistently underestimates the value of Δ_y and overestimates the value of F_y as a result of using an idealised elastic plastic relationship with the constraint of matching the energy dissipation of the model and the data [124].

The K&C model defines F_y as simply 0.5 F_{max}. Displacement at yield, Δ_y, is simply displacement, Δ, at the point where 0.5 F_{max} occurs. This relationship is illustrated in Figure 5-16a. The Y&K model, similar to the European model, bases F_y and Δ_y on the intersection of two lines defined around points on the load slip curve. In the Y&K model, the first line passes through the points at which 0.1 F_{max} and 0.4 F_{max} occur, the same as the model in [116]. The second line lies tangent to the load slip curve and parallel to a line passing through the points at which 0.4 F_{max} and 0.9 F_{max} occur. This second line is found by first constructing the line that joins the points 0.4 F_{max} and 0.9 F_{max}. This line is then translated upwards until the point at which it lies tangent to the load slip curve is found. The major difference between the Y&K model and the European model is that in the Y&K model, the intersection of the two definition lines is then projected back onto the actual load slip curve. This means actual values from the loading data are used to determine yield strength, preventing Δ_y being underestimated. The Y&K relationship is illustrated in Figure 5-16b.

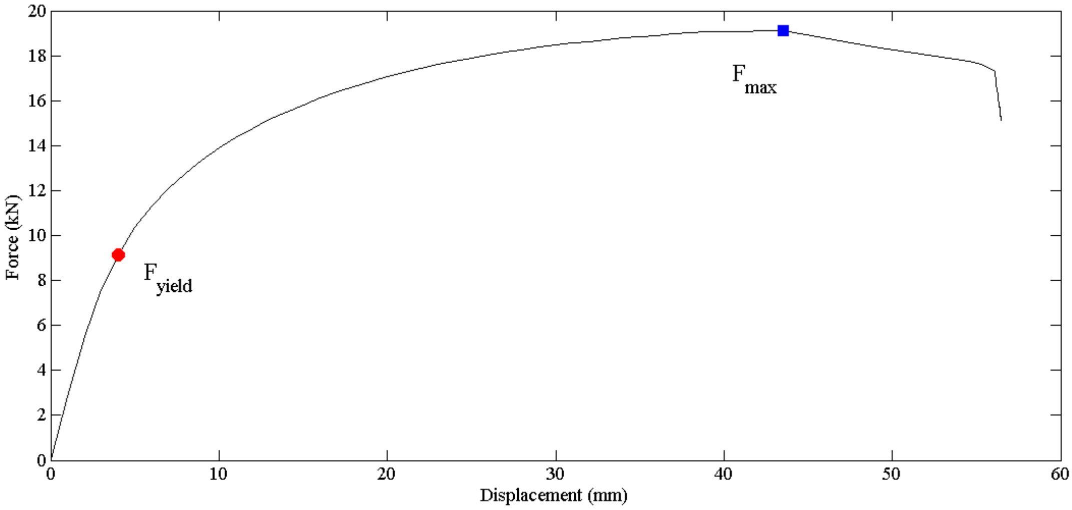
Table 5.4: Comparison of the values for yield strength given by the two models. F_y is the yield strength in kN.

Condition	$F_{y,K\&C}$ (kN)	CoV (%)	$F_{y,Y\&K}$ (kN)	CoV (%)
Control	09.2	3	10.3	11
Wet	07.3	2	08.2	02
Restored	06.8	11	07.9	12

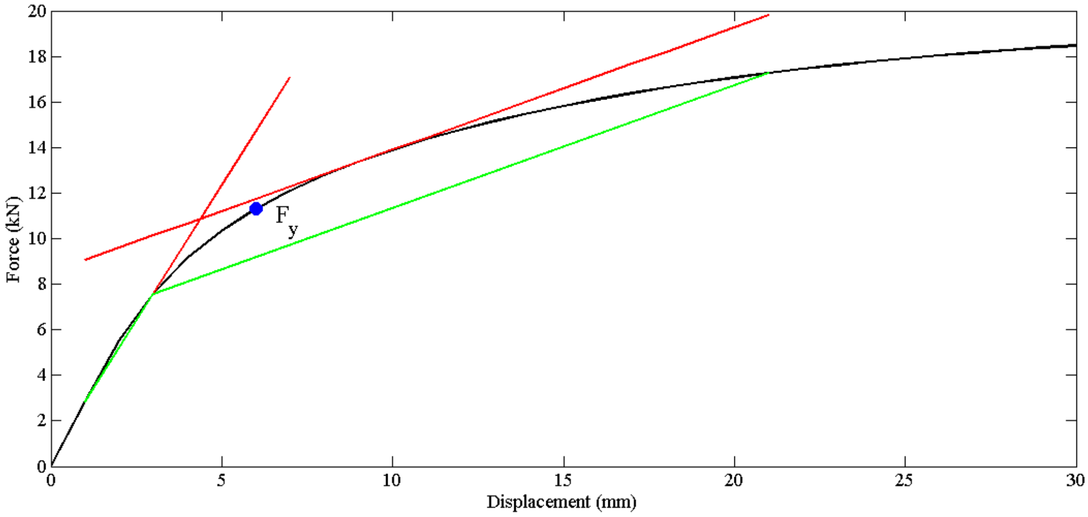
Table 5.5: Comparison of the displacement at yield, Δ_y, calculated by each model.Δ_y is given in mm.

Condition	$\Delta_{y,K\&C}$ (mm)	CoV (%)	$\Delta_{y,Y\&K}$ (mm)	CoV (%)
Control	5.3	43	6.3	24
Wet	5.0	01	6.1	05
Restored	5.3	63	6.5	48

As expected, the two models produce different values of yield strength for the walls. Yield strength, F_y, for each wall condition is given in Table 5.4. Yield displacement, Δ_y, is given in Table 5.5. Using the K&C model gives lower values of F_y for all walls however, there is less variation in the results. The Y&K model returns higher values of F_y but with greater variation. For Δ_y, the Y&K model again returns higher values but the variation is reduced significantly.



(a) The Karacabeyli and Ceccotti yield model.



(b) The Yasumura and Kawai yield model.

Figure 5-16: Graphical representations of the two different yield models used to determine yield strength of the shear walls tested. Fig. 5-16a is the Karacabeyli and Ceccotti yield model [125] and Fig. 5-16b is the Yasumura and Kawai model [126].

Although the exact results differ depending on the yield model used, a similar trend is present for both models. That is, condition 2 and 3 walls have reduced yield strength compared to condition 1. Furthermore, there is little difference between the wet specimens and the restored specimens in terms of yield strength.

ANOVA analysis indicates that there is a difference between means. For the Y&K model; [$F(2,6) = 6.5$, $p = 0.03$]. For the K&C model; [$F(2,6) = 23.1$, $p = 0.002$]. Post-hoc analysis via pairwise t-testing shows a similar trend as observed in Section 5.3.3; the wet and restored specimen means are not significantly different from each other, see Table 5.6.

Table 5.6: Pairwise t-test comparison for shear wall yield strength, F_y. For both yield models, the wet and restored specimen means are not significantly different from one another. The t-test was single tailed, using the Holm p adjustment method.

Condition	p K&C	p Y&K
Control - Wet	0.0024	0.028
Control - Restored	0.00097	0.024
Wet-Restored	0.8997	0.657

5.3.5 Initial stiffness

The initial stiffness of the specimens is defined as the secant stiffness between 0.1 F_{max} and 0.4 F_{max}, [122]. Initial stiffness, k_i, is given in Table 5.7 and is in kN/mm. There is a noticeable drop in the wall stiffness for conditions 2 and 3 compared to the control specimens. The restored specimens are stiffer than the wet specimens. Restoration of the walls by drying has recovered some of the original stiffness.

5.3.6 Ductility

Ductility is a measure of how much deformation a structure can undergo without a substantial reduction is strength. Ductility, μ, is defined as the ratio of the

Table 5.7: Mean initial stiffness of the shear walls tested. Both condition 2 and three walls have reduced stiffness in comparison to the control walls. Note the large CoV for condition 3.

Condition	$\overline{k_i}$ (kN/mm)	CoV (%)
Control	2.46	36
Wet	1.15	27
Restored	1.63	53

displacement at the maximum load to the displacement at yield [116]:

$$\mu = \frac{\Delta_{max}}{\Delta_{yield}} \tag{5.1}$$

As was mentioned in Section 5.3.4, the definition of yield strength has an effect on the calculated value of ductility of a structure. Ductility has been calculated using the Δ_y values generated by both yield models studied in Section 5.3.4 (Table 5.5). The values for displacement at ultimate strength, Δ_u, are given in Table 5.3. The averaged ductility ratios, μ, for each wall condition tested are given in Table 5.8. In Table 5.8, μ is the ratio of the mean displacement at $\mathrm{F_u}$ to the mean displacements at $\mathrm{F_y}$ for each condition. That is; $\overline{\mu} = \frac{\overline{\Delta_u}}{\overline{\Delta_y}}$. The coefficient of variance in this case is estimated using the "delta method".

Table 5.8: Comparison of ductility ratios, μ, of the tested wall specimens. μ has been calculated using Δ_y from from both yield models studied in Section 5.3.4.

Condition	$\mu_{K\&C}$	CoV (%)	$\mu_{Y\&K}$	CoV (%)
Control	8.5	26.6	7.1	05.5
Wet	7.0	6.6	5.7	05.1
Restored	6.6	49.1	5.4	33.6

There are noticeable differences between the values of μ calculated using values from each yield model. Using values of Δ_y derived from the Karacabeyli and Ceccotti yield model results in consistently greater ductility values than when the values from the Yasumura and Kawai model are used. In addition to a greater value of μ, the coefficient of variation is also significantly larger when using values from the K&C model, $> 49\%$ for the restored specimens and $> 26\%$ for the control. In contrast, the Y&K model has a CoV of approximately 5% for the control and wet specimens. Although the CoV for the restored specimens is high, 33%, it is less than for the K&C method.

In [127], suggested ductility classes are provided based on the value of μ. For $4 < \mu \leq 6$, the structure is defined as moderately ductile and for $\mu > 6$ the structure is classified as highly ductile. According to the K&C model, all the walls tested are classified as highly ductile ($\mu > 6$, see Table 5.8). The Y&K model classifies the walls differently, with only the control specimens classified as highly ductile. Both the wet and restored walls drop a ductility class and become "*moderately ductile*". As a result, the calculations of μ based on the Y&K method are a better fit for the experimental data.

5.3.7 OSB and timber displacement

Measurements were taken of displacements of the trailing side of the wall during loading. The OSB and the timber stud were monitored independently of each other. Transducers are in pairs, one monitoring timber displacement and one monitoring OSB at each measurement location. Five LVDT's were used to measure timber displacement via direct contact with the vertical stud. These transducers were located at vertical locations $z = 0$ m, $z = 0.5$ m, $z = 1.0$ m, $z = 1.4$ m and $z = 1.8$ m. Metal brackets were fixed to the OSB with contact adhesive at the same height as the timber LVDT's. A second line of five LVDT's monitored the displacement of the metal brackets, and by proxy the OSB, during loading. The wall can be split into two imaginary sections; the wetted section below the simulated flood level and the dry section above the flood level. There are two transducers located on both the upper and lower wall sections and a final transducer located at the water line on the walls. Comparison of the progressive displacement data allows differences in the wall conditions to be explored.

Differential OSB and timber displacement

The data show that the OSB and timber displace relative to each other. Figure 5-17 shows displacement data during loading for each transducer. In Figure 5-17, the solid lines represent the OSB displacement and the dashed lines represent the timber displacement. Lines are paired so that the timber and OSB displacement measurements from the same vertical locations are grouped. The top pair of lines, marked +, represent the upper most pair of LVDT's, the middle lines, marked Δ, represent the middle LVDT pair and so on. It can be seen that the Timber displaces more than the OSB in all cases except for at the location of the lowest LVDT pair; at the foot of the wall. Except for the lower pair, the dashed line is always above the solid line. The difference between the displacement of the OSB and timber decreases as the measurement height decreases. At the foot of the wall the OSB displaces more than the timber. In fact, at the foot of the wall, the timber shows almost no displacement at all.

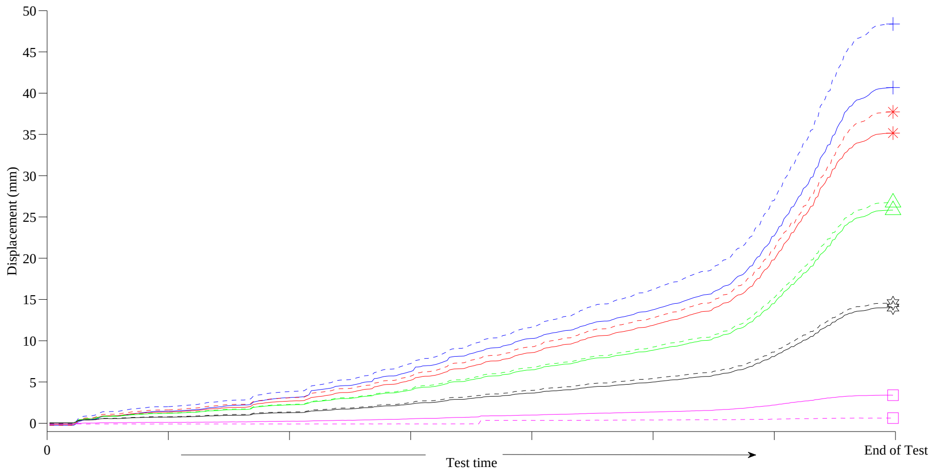
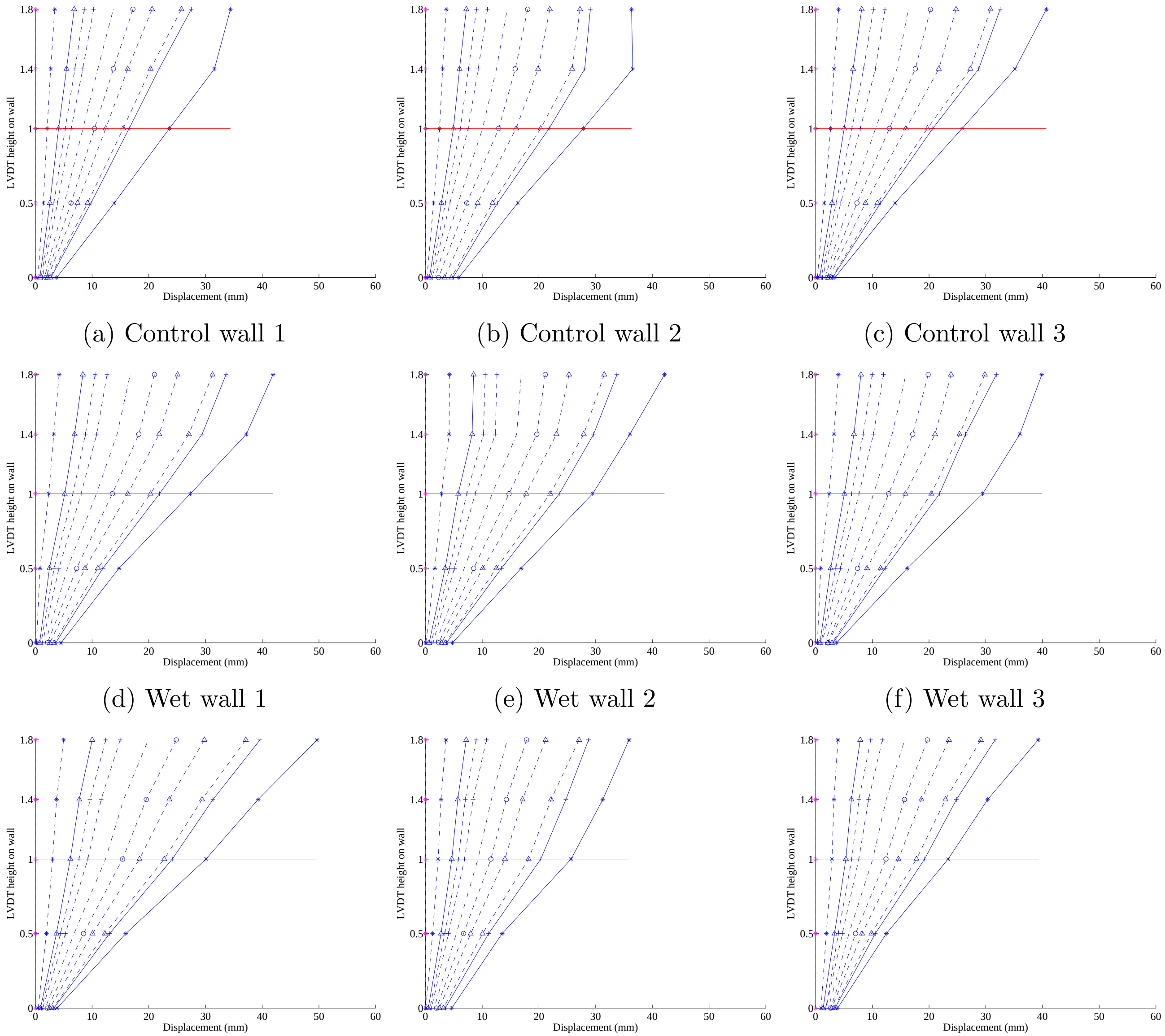


Figure 5-17: Displacement data from the trailing side of a shear wall for OSB and timber. The OSB displacements are represented by the solid line, the timber by the dashed. The upper most pair of lines (+, blue) is the upper most pair of LVDTs. The middle line pair (Δ, green) represents the middle LVDT pair and so on. The timber is always displaced more than the OSB apart from at the foot of the wall.

OSB displacement

Figure 5-18 shows the displacements of the OSB recorded at various points along the trailing edge of the wall. Each individual line represents a fractional increase of the wall displacement. Figure 5-18 is in effect a representation of the shape of the board edge as displacement increases.



(a) Control wall 1 (b) Control wall 2 (c) Control wall 3

(d) Wet wall 1 (e) Wet wall 2 (f) Wet wall 3

(g) Restored wall 1 (h) Restored wall 2 (i) Restored wall 3

Figure 5-18: Displacement of OSB sheathing. Each vertical line shows the progress of recorded displacements from LVDT's located on the walls trailing edge. The horizontal line (red) shows the depth of flooding on the walls. The flood depth line is included on the control wall data for the purpose of comparison.

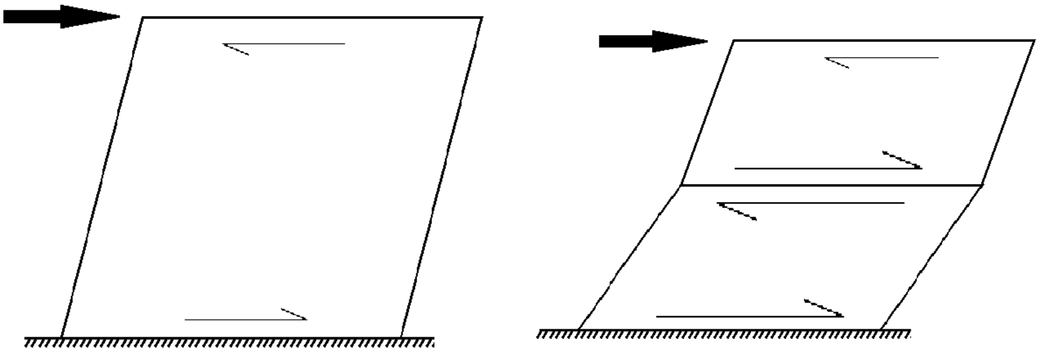
When dry, the OSB sheathing has approximately uniform material properties and acts as a solid, uniform body. Displacement should therefore be linear along the entire board edge and the gradient between measurement locations will be the same. For the control wall data, Figs. 5-18a - 5-18c, this is the case. This displacement along the edge of the board is almost perfectly linear.

Deviations in this pattern as the displacement increases are a result of the LVDT losing contact with the OSB at the upper measurement location, Figs. 5-18b and 5-18c. The metal brackets attached to the OSB either detached or, the LVDT slipped away from the bracket as it became misaligned during displacement.

For the wet specimens, there is a discrepancy in the displacements between the upper and lower section of the wall, Figs. 5-18d to 5-18f. The three measurement locations below the waterline, $z = 0$ m, $z = 0.5$ m and $z = 1.0$ m have an approximately linear line joining them. The same is true of locations above the waterline, $z = 1.0$ m, $z = 1.4$ m and $z = 1.8$ m. The two sections of the wall above and below the waterline, do not however, have the same gradient between the displaced points.

The lower section of the wall appears to have a less steep displacement gradient than the upper, suggesting that it has lower stiffness compared to the upper section of the wall. This indicates that the wall sheathing no longer acts as a uniform body. Instead, the upper part of the sheathing appears to be shearing across the lower section. This is illustrated in Figure 5-19. In Fig. 5-19a, the sheathing acts as a uniform body. Figure 5-19b illustrates what happens when then board is wetted; the difference between the top and bottom sections of the board can be seen.

The upper section shears over the less stiff lower section. This difference between the wet and control specimens is illustrated in Figure 5-20. Figure 5-20 shows the data for a wet wall and a control wall overlayed. The wet wall is represented by the solid line (red) and the control wall is represented by the dashed line (blue). At low displacements there is little difference between the control and wet walls however, as displacement increases, they diverge. The wet wall begins to show a change in stiffness between the upper and lower sections of the wall that the control wall does not.



(a) Dry OSB. (b) Wet OSB.

Figure 5-19: Diagramatic representation of differential OSB displacements. Dry OSB, Fig. 5-19a, is displaced as a solid body. Wet OSB, Fig. 5-19a, exhibits differential displacement due to different material properties along the board height.

In the restored walls, drying enables the sheathing to return to acting as a uniform body. The displacement of the sheathing board follows approximately the same gradient in both sections of the wall. As a result of this OSB behaviour, failure would be expected to occur first in the nailed connections in the lower section of the wall.

Walls were monitored during loading by a digital camera programmed to take an image every 5 s. Comparing the connection displacement of the upper and lower sections of the wall allows the confirmation of this behaviour. Figure 5-21 illustrates the timber to sheathing connection displacement of a control wall. The overall displacement is small and displacement is approximately equivalent for both upper and lower sections at failure. Figure 5-22 illustrates the timber to sheathing connection displacement of a wet wall. The images focus on the areas around the top and bottom rail and were captured at the same time. The difference in displacement between the upper and lower sections can be clearly seen. The connections in the lower section have displaced much more than those in the upper section and more nailed connections have failed.

In Figure 5-21 the displacement of the OSB relative to the timber is limited. The displacement at the nails labelled 2 and 4 is very small. Nails 1 and 3 in equivalent locations in the top and bottom of the wall are in OSB that is displaced

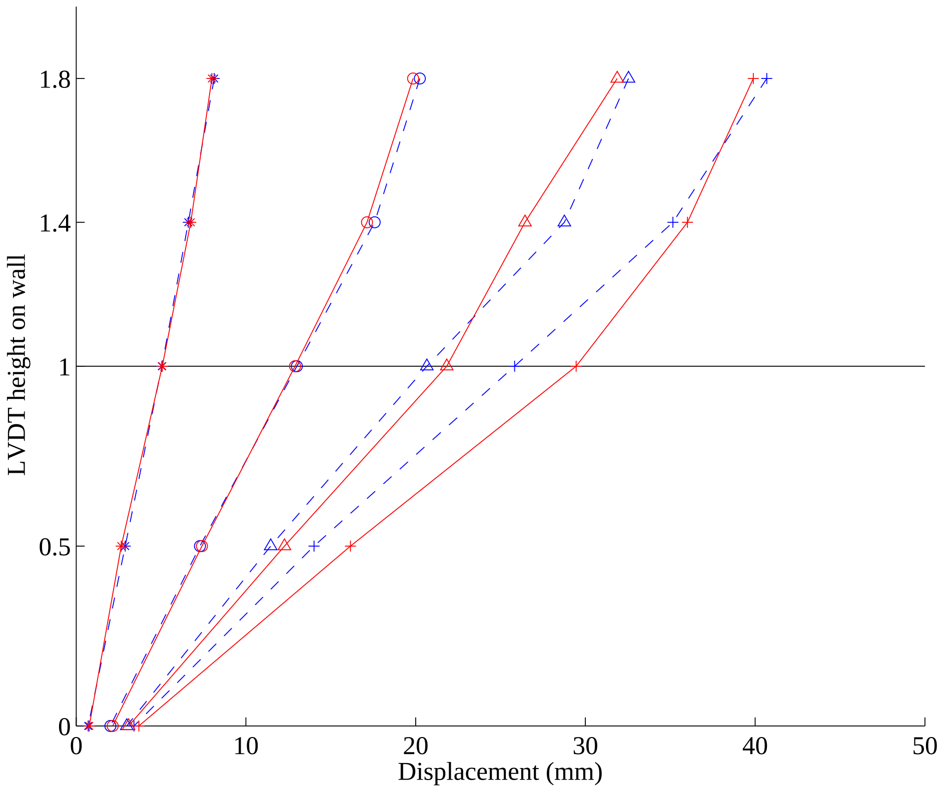


Figure 5-20: Comparison of OSB displacements in the control walls and wet walls. The control wall is represented by the dashed line (blue) and the wet wall is represented by the solid line (red). The divergence between the two specimens is visible as the displacement increases. The upper and lower sections of the wet wall are clearly illustrated by the change in stiffness between the section that was flooded and the section that remained dry.

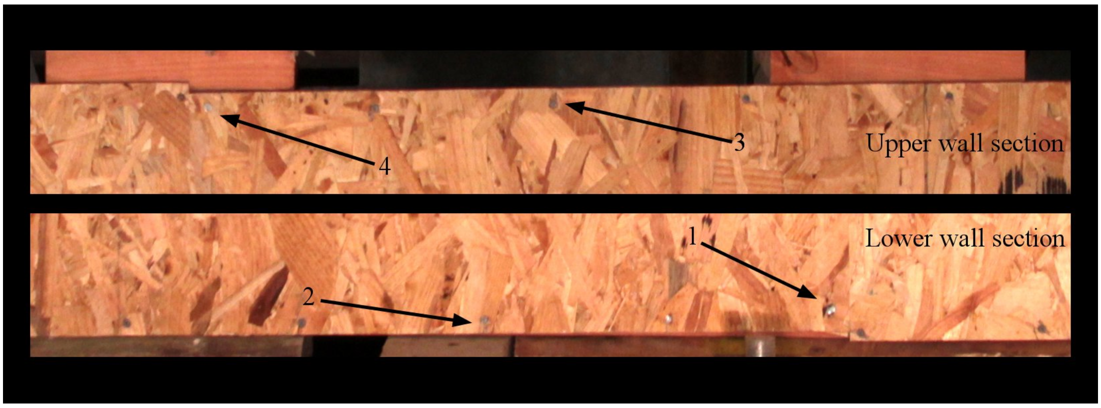


Figure 5-21: Comparison of connection displacement in the upper and lower section of a control wall. The connection displacement is equivalent in the upper and lower sections of the wall at failure.

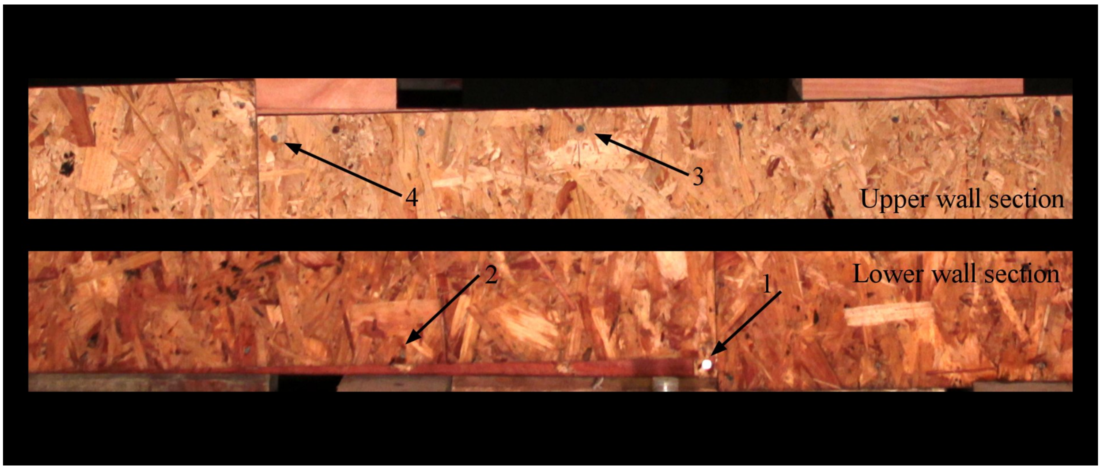


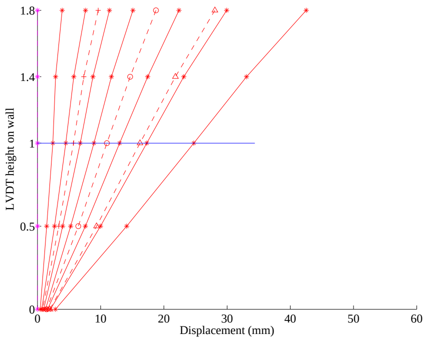
Figure 5-22: Comparison of connection displacement in the upper and lower section of a wet wall. The connection displacement is different in the upper and lower sections of the wall at failure. The connections in the lower, wetted section have failed before those in the upper section.

by approximately the same amount; there is no visual difference. Compare this to the displacements illustrated in Fig. 5-22. There is a clear visual difference between the upper and lower sections of the wall. Nails 1 and 2 are in OSB that is displaced significantly more than at the location of nails 3 and 4. Nail 1 has fully ripped out whereas Nail 4 is still embedded in the OSB. More of the connections along the base of the wall have ripped out in Figure 5-22 than in the top section of the wall. These images taken at the wall failure help confirm the idea that the sheathing on the wet walls is less stiff in the lower section and that failure occurs in the wetted portion of the wall.

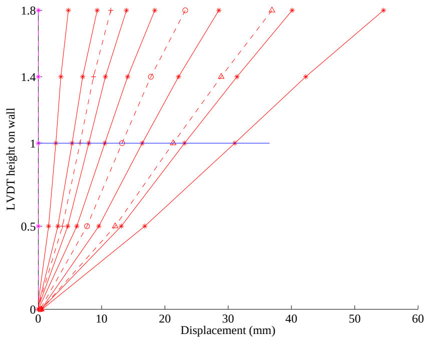
Timber displacement

A similar chart to that seen in the previous section is produced for the timber displacement data, Figure 5-23. The major difference is the lack of displacement recorded at the foot of the wall, the transducer at $z = 0$ m. Apart from some minimal sliding of control wall 1, the timber does not displace at the foot of the wall. Instead it rotates about this point. Furthermore, the timber always displaces as a solid body. There is no difference between the top and bottom sections of the wall with respect to the timber displacement. The gradient between measurement locations is always the same. Unlike for the OSB, the timber displacement data does not indicate that differential displacement is occurring due to flooding changing the material properties of part of the structure. The timber frame acts as a pinned mechanism, rotating about the connections between its horizontal and vertical components.

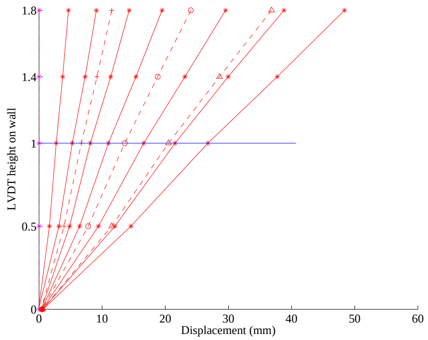
These data show that it is indeed the sheathing providing the lateral resistance in timber frames walls. The OSB is affected by the flooding and no longer acts as a solid body. Instead, the unflooded section shears over the flooded section. Nailed connection failure occurs in the lower section of the wall where it has been exposed to water.



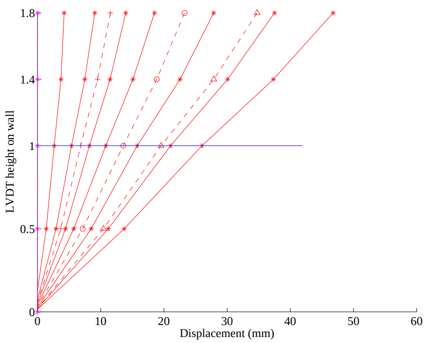
(a) Control wall 1



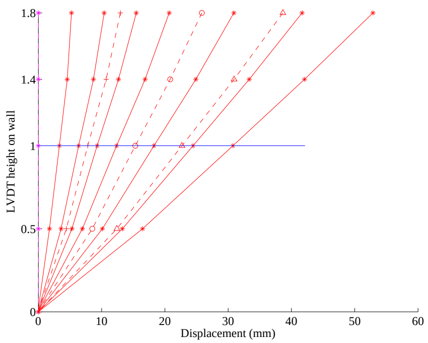
(b) Control wall 2



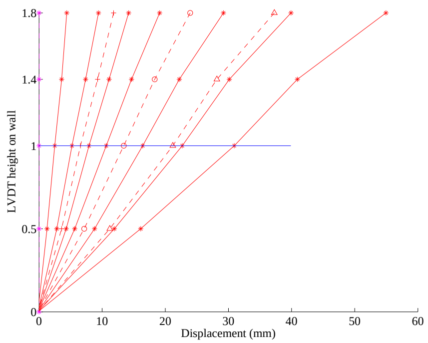
(c) Control wall 3



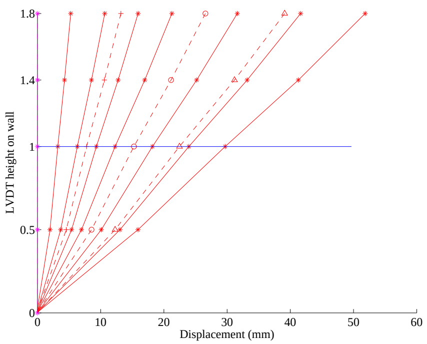
(d) Wet wall 1



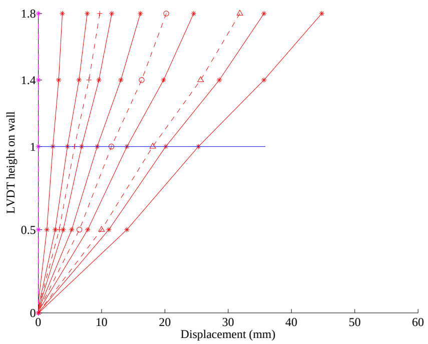
(e) Wet wall 2



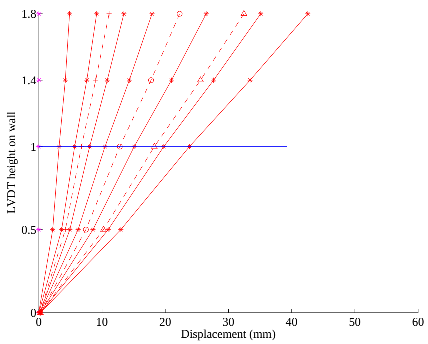
(f) Wet wall 3



(g) Restored wall 1



(h) Restored wall 2



(i) Restored wall 3

Figure 5-23: Displacement of trailing timber stud on trailing side of wall. Each individual vertical line shows the progress of recorded displacements from LVDT's located on the walls trailing edge. The horizontal line (blue) shows the depth of flooding on the walls. The flood depth line is included on the control wall data for the purpose of comparison.

5.4 Comparison to existing models

In this sections the results are fitted to existing models. Two design models are considered; the Källsner and Girhammar plastic model [46] and the PD 6693-1 model [41].

5.4.1 Källsner and Girhammar model

As is discussed in Chapter 2, Section 2.4, the design method for shear walls in the UK [41] and in Eurocode 5 [53] is based on the Källsner and Girhammar plastic model [46]. The model uses the plastic connection capacity of the sheathing to timber connections, f_p in order to calculate the plastic racking capacity of the wall, H.

Using Källsner and Girhammar's 2004 model [46], and values of f_p derived from the connection tests in Chapter 4, predicted racking strength values for the conditions studied here are generated. The plastic connection capacity is calculated according to Eqn. 5.2:

$$f_p = \frac{\mathrm{F_u}}{nail\ spacing} \tag{5.2}$$

where $\mathrm{F_u}$ is the mean maximum strength of the sheathing to timber connection calculated in Chapter 4. Källsner and Girhammar give a number of versions of their model in their 2004 paper. The version used here is the final version they present in which moments are taken about the entire wall. This model requires an iterative process to determine the correct failure value. This model also accounts for the horizontal shear capacity of the timber to timber joints. Values for the horizontal shear capacity of the timber to timber joints are taken from Källsner and Girhammar [46] as 2 kN. The model outputs are given in Table 5.9. For most cases the iterative solving process returns only one valid solution. Where this is not the case, the solution with the highest value of k and β_L has been used.

From Table 5.9 it can be seen that the model tends to over-predict the racking strength of the tested walls. The wet specimens have the closest match between predicted and measured loads. The strength of the control walls is over predicted by 29% and the restored walls are over predicted by 37%.

Table 5.9: Predicted theoretical racking strengths of the tested walls. Values of f_p are derived from data in Chapter 4.

Condition	f_p (kN/m)	$H_{predicted}$ (kN)	$H_{measured}$ (kN)	$\frac{H_{predicted}}{H_{measured}}$
Control	12.4	23.6	18.2	1.3
Wet	06.9	14.7	14.7	1.00
Restored	08.7	18.2	13.8	1.4

5.4.2 PD 6693 Model

The UK design code, PD 6693-1 [41], was introduced in Chapter 2, Section 2.4.2. Here, the design code is used to model the tested walls. There are a number of assumptions that must be made in order to apply this design model to the experimental results.

The first assumption concerns the parameter μ. This is defined in PD 6693-1 as the ratio of the anchorage withdrawal capacity to the capacity of the sheathing to timber fasteners. In these calculations it is assumed that $\mu = 1$, its maximum allowable value. The second assumption concerns the value of the nailed connection capacity, $f_{p,d,t}$. Rather than follow the procedure described in the design code for calculating the mean value of the sheathing to timber fastener capacity based on the characteristic value, the mean values calculated from the connection tests in Chapter 4 are used. The actual values for $f_{p,d,t}$ are the same as those used for f_p in Section 5.4.1, Table 5.9. Finally, an assumption must be made regarding the value of $M_{d,stb,n}$. This term is supposed to be the net stabilising moment acting on the wall. It is calculated by subtracting the destabilising moment acting about the wall, generally wind loading, from the stabilising moment produced by vertical loads along the top of the wall. Since there is no external force other than that applied to the wall in the tests it is assumed that there is no destabilising moment. As such, $M_{d,stb,n}$ is equal to the stabilising moment due to external vertical loads. In this case therefore, $M_{d,stb,n} = 30$ kNm.

Since the walls do not contain openings and are only sheathed on one side, the values for $K_{opening}$ and K_{comb} are 1 and 0 respectively. With these assumptions in place the strength of the walls can be calculated. The results are given in Table 5.10. It can be seen that the model again over-predicts the strength of the tested walls. Apart from the wet specimens, the ratio of measured to predicted strength is similar to that recorded for the Källsner and Girhammar model in section 5.4.1. For the wet specimens, agreement between the measured and predicted strengths was good using the Källsner and Girhammar model. Using the PD 6693-1 model however, leads to an over prediction in strength of 13%.

Table 5.10: Predicted strengths of the test walls according to the design code PD 6693 [41].

Condition	$H_{Predicted}$ (kN)	$H_{Measured}$ (kN)	$\frac{H_{Predicted}}{H_{Measured}}$
Control	23.8	18.2	1.3
Wet	16.6	14.7	1.1
Restored	19.0	13.8	1.4

5.5 Conclusions

The results presented in this chapter show that there is a permanent loss in the mechanical properties of a timber shear wall as a result of flooding and subsequent restoration. The results are summarised in Table 5.11.

Ultimate strength was seen to reduce by 20% for wet walls and 25% for the restored walls. Yield strength reduced by a similar amount. Ductility of the walls was also reduced, with both condition 2 and 3 walls dropping a ductility class from 'highly ductile" to "moderately ductile". A loss of stiffness was also observed, with wet walls just 47% of their original stiffness, and restored walls 66% of their original stiffness.

The most significant factor is the change in the wall failure behaviour. The restored walls have a tendency to fail due to out of plane buckling of the sheathing board. This change in failure mode is not accounted for by current design documentation.

The experimental results were not in good agreement with the results predicted by the Källsner and Girhammar or PD 6693-1 models. The control specimens had 29% less ultimate strength than predicted and restored specimens 37% less according to the Källsner and Girhammar model. Only the wet specimens were

Table 5.11: Summary table of the mean mechanical properties derived fro the shear walls tested. Mean values of ultimate strength, F_u, yield strength, F_y, initial stiffness and ductility, μ are given for each of the walls conditions tested.

	Strength		Stiffness	Ductility	
Specimen	F_u (kN)	F_y (kN)	k_i (kN/mm)	μ	Classification
Control	18.2	10.3	2.5	7.1	Highly ductile
Wet	14.7	08.2	1.2	5.7	Moderately ductile
Restored	13.8	07.9	1.6	5.4	

in good agreement with the model. For the PD 6693-1 model, the strength of all conditions were over-predicted.

The key findings of the chapter can be summarised as follows:

- Flooding causes a permanent reduction in the mechanical properties of the walls.
- Strength, stiffness and ductility are all reduced as a result of flooding.
- Stiffness is partially recoverable by drying, but there is still a permanent loss.
- Curvature of the sheathing board was observed in the restored walls.
  - This results in out of plane behaviour leading to buckling of the sheathing.
- The buckling failure is not considered by design codes or the models they are based on.
- The Källsner and Girhammar and PD 6693-1 models do not have good agreement with the data.

The results presented here are discussed in the following chapter.

Chapter 6

Discussion of shear wall tests

The results presented in the previous chapter are discussed in the following sections.

6.1 Strength

The ultimate and yield strengths of the walls, Chapter 5, Sections 5.3.3 and 5.3.3, show that there is a decrease in wall strength as a result of flooding. The wet specimens are, on average, 20% weaker than the control specimens tested with respect to F_u. Similarly, the restored specimens are weaker by an average of approximately 25%. Yield strengths, as derived by the Yasumura and Kawai model, are also reduced by a similar amount. These data shows that the structure has experienced a permanent loss in strength due to flooding; following drying wall strength is not fully recovered. This permanent loss is in agreement with the results of Chapter 4. In contrast to the Chapter 4 results, the restored wall specimens have lower strengths than the wet specimens in terms of both F_u and F_y. A mechanism for this behaviour is proposed in Section 6.5. The differences in variation of strength are addressed in this section.

6.2 Stiffness

When exposed to simulated flooding, the stiffness of the walls was seen to reduce. Both condition 2 and 3 walls had a lower stiffness than the control walls tested. The condition 2 walls (wet) exhibited the lowest stiffness, with the condition 3 walls (recovered) experiencing a small recovery in stiffness after drying.

The recovered walls, condition 3, are approximately 34% less stiff than the control walls. The wet walls, condition 2, have a stiffness of just 47% of the control walls.

In Chapter 4, the point was made that the connection stiffness may not accurately represent the wall stiffness and this is seen in the results presented in Chapter 5. The complete shear wall assembly is more complex than the connections that were tested and reported in Chapter 4 and has more scope to generate stiffness. In the connections studied, stiffness was a result of a single nailed connection. Swelling of the OSB or timber and friction between the specimen components has little impact on the stiffness. Initial stiffness was derived from the nail bearing into the timber and OSB as they displaced relative to each other.

In the shear wall, generation of stiffness is more complex. There are a number of contributing sources of stiffness. Firstly, the shear stiffness of the OSB sheathing is the primary source of wall stiffness. In addition, multiple connections between the sheathing and timber along the perimeter contribute to the stiffness, as do the nailed connections along the internal studs.

The framing joints are also a source of stiffness in the system. The connection between the vertical timber studs and horizontal rails have some horizontal shear capacity [46, 47] that contributes to the wall stiffness. These additional stiffness sources are more sensitive to the effects of wood swelling than the single connections. Swelling in the timber and the OSB has a greater impact on the whole wall stiffness than it does on the stiffness of the single nailed connections.

Taking the framing joints as an example, swelling of the timber due to flooding will cause these joints to pull apart. When dried, although the timber will recover to close to its original dimensions and material properties, the joints will remain "pulled apart". This will contribute to a permanent loss of stiffness that is not fully recovered by drying.

It is worth noting that unlike strength, wall stiffness was partially recovered by the drying process. The restored walls are approximately 41% stiffer than the wet walls. Neither Eurocode 5 nor PD 6693-1 give design guidance relating to the wall stiffness. These results are therefore an important indication of the impact that flooding has on the stiffness of shear wall assemblies.

6.3 Ductility

The ductility of the walls was reduced by flooding and subsequent drying. Table 5.8 in Chapter 5 shows that the condition 2 and 3 specimens drop a ductility class due to the wetting and drying process. Ductility drops from "Highly Ductile" to "Moderately Ductile" [127]. Flooding and the subsequent drying process not only permanently reduce the strength and stiffness of the structure but its ductility also.

6.4 Model discrepancies

In Chapter 5, Sections 5.4.1 and 5.4.2, the measured wall strengths were compared to the theoretical strengths of the walls according to the Källsner and Girhammar model and the PD 6693-1 model.

As shown in Table 5.9 and Table 5.10, the models tend to over predict the strengths of the walls. Only the strengths for the wet walls, using the Källsner and Girhammar model, were in good agreement with the experimental values.

There are a number of possible explanations for the discrepancies between the model and experimental results:

- Sheathing buckling.
- Manufacturing error.
- Model inaccuracies and assumptions.

6.4.1 Sheathing buckling

The results given in Chapter 4 suggest that the wet walls would be weaker than the restored walls. This is because the restored specimens have greater mechanical properties than the wet connection specimens. The results for shear walls presented in Chapter 5 show that this was not the case. The mean strength of the wet walls was slightly greater than that of the restored walls. One possible explanation for this, and for the model discrepancies observed for the condition 3 walls, is the sheathing buckling, see Chapter 5, Section 5.3.2. Failure of the restored walls occurs as a result of out of plane actions in the sheathing, something that neither model accounts for. The out of plane action leads to a discrepancy between the modelled values and experimental results. This out of plane behaviour is discussed further in Section 6.5.

6.4.2 Manufacturing error

During construction of any shear wall it is possible that manufacturing errors will be made. In the case of the walls tested here, it was noticed that a number of nails were misfired, see Figure 6-1.

Nail misfire can occur for a number of reasons;

- Nail gun not perpendicular to the surface when fired.
  - Nail is fired at an angle that leads to the point side exiting the side of the stud.
- Nail encounters a change in density of the timber as it passes through the stud.
  - Results in the nail bending and the point penetrating the side of the stud.

In both cases, the misfire leads to the sheathing board being incorrectly fixed to the frame and results in a loss of connection capacity.

Nails are fired from the nail gun with enough force to drive them into the timber in a single motion. Any change in density of the timber such a knot or difference

(a) Example of a misfired nail. The nail gun was not perfectly aligned with the frame and the point of the nail has exited the timber frame member to the side, reducing the connection strength.

(b) Examples of misfired nails along side of panels. Points of nails are covered by protective foam to prevent then catching or injuring anyone during transport. These misfires are a result of changes in timber density causing the nail to bend as it passes through the member.

Figure 6-1: Examples of misfired nails. In Fig 6-1a shows the detail of a misfired nail. Figure 6-1b shows a number of misfired nails along the side edge of a panel.

in growth ring spacing can result in the nail bending and deviating from its course. Similarly, if the nail gun is not perfectly level with the timber surface, the nail can misfire, with the nail point penetrating out the sides of the timber member. It is also possible for the pressure the nailfrom the gun which fires the nail to vary due to slight reductions in gas pressure. This can also lead to the nail bending in the timber as it does not have adequate driving energy.

Nail misfire, leading to incorrect fixing of the wall sheathing, is a risk when the walls are assembled by hand, as these specimens were. The Källsner and Girhammar model assumes that all nails are a perfect connection between the sheathing and timber however, with misfired nails present, this is not the case. The exact number of nails misfired during construction of the walls was not recorded.

Other possible sources of manufacturing error include, but are not limited to:

- Nails that miss the studs in the timber framing.
- Incorrect or inaccurate nail spacing.
- Incorrect or variation in edge distance of nails.
- Induced framing forces due to incorrect geometry or misalignment of members during assembly.

These errors could occur in any manufactured wall, especially those constructed by hand, and the issues of nails missing framing members is common. Each of these errors will reduce the strength of a wall from its ideal modelled capacity.

6.4.3 Model error and assumptions

There is the possibility that there are errors in model assumptions and in the validity of the models used that could lead to discrepancies between predicted and experimental results.

The Källsner and Girhammar model was verified against limited tests performed on shear walls sheathed in a variety of materials; hardboard (predominantly), plywood, particleboard [47] and fibreboard [45]. The tests did not investigate the validity of the model when used for walls clad in OSB sheathing. As such, the model may be less accurate for walls sheathed in OSB. For the PD 6693-1 model, a number of assumptions were made about parameters such as $M_{d,stb,n}$ and μ that may introduce inaccuracies. It is also worth noting that the model was used in a manner in which it was not intended. It is a design model, not a tool for experimental verification. A design model must produce safe predictions and therefore includes load factors and other factors of safety whereas experimental verification must accurately predict capacity.

6.4.4 Summary

There are number of possible reasons for the discrepancy between the experimental and predicted results. From observing the shear wall tests, it is likely that the buckling failure of the sheathing in the condition 3 walls plays a major role in the reduced capacity of the restored specimens. It is not possible to quantify the effect that manufacturing error, specifically the nail misfire, had on the walls tested although it is no doubt an important aspect. It is worth noting that manufacturing errors are a common issue when constructing by hand or assembling on site, especially the phenomenon of nails missing framing studs. Finally, it is not the purpose of this study to attempt to verify the accuracy or validity of the existing design models. It is an area that is worthy of future study however, it is beyond the scope of this project. This study is concerned only with the effects of flooding on shear walls. A specific investigation with more test specimens would be required to correctly address the points raised.

6.5 Out of plane behaviour

In Chapter 5, Section 5.3.2, the out of plane buckling behaviour observed in the walls was introduced. The sheathing, when exposed to water, swells and, because of the restraint of the nail line, bends rather than simply expanding.

In Eurocode 5 and PD 6693-1 a sheathing buckling check is given:

$$\frac{b_{net}}{t} \leq 100 \tag{6.1}$$

where b_{net} is the spacing between vertical studs and t is the sheathing thickness, both expressed in mm. As long as the ratio of b_{net} to t is less than 100, the wall is considered to be adequately designed to resist buckling of the sheathing board. For all walls tested, this criterion is met. The original design has $t = 9$ mm and $b_{net} = 600$ mm, giving a ratio of 66.66. When wetted the sheathing swells to between 11 and 12 mm. This results in a ratio of 55-50. The assumption of the code is that the thicker the sheathing, the less likely it is to buckle, hence the improvement in the ratio given by Eqn. 6.1. This check however, is intended for flat, undamaged sheathing. Indeed, undamaged 12 mm OSB board is less susceptible to buckling than 9 mm OSB. This is not true however, in the case of the walls that have been flooded.

In Chapter 4, Figure 4-9a shows the extent of damage flooding can cause to the sheathing. Previous work, [80–82], has also shown the damage that an increase in MC causes to OSB. As shown in Figure 5-12, the sheathing is not flat nor is it undamaged.

After a flood, the wall sheathing is not flat, nor is it undamaged. Instead, it is curved away from the plane of the wall, see Fig. 5-12, and has a reduction in inter-layer strength due to swelling rupturing the adhesive between layers. As a result, when loaded, significant out of plane behaviour is to be expected. The curvature in the board is an initial imperfection. Loading of the sheet is therefore eccentric to the plane of the sheet, Fig 6-2. This eccentric loading results in moments in the sheet which reduce the buckling resistance. The swelling induced rupture to the OSB interlayer bonds also reduces the Young's modulus, again resulting in a reduction to the buckling resistance.

Impact on wall behaviour

It is proposed that this out of plane buckling is responsible for reduction in strengths observed for the condition 3 (restored) walls. They are weaker than the

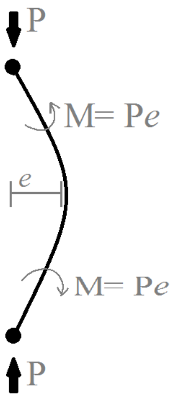


Figure 6-2: Bending moments in the sheathing due to OSB curvature. The curvature causes eccentric loading, reducing the sheets bucking resistance. Section of sheet is between two studs and viewed top down.

wet walls, despite the fact that their sheathing to timber connection strength is greater, as shown in Chapter 4. Although the difference in wall strength between the two conditions is low, the results from Chapter 4 suggest that the restored walls should be significantly stronger than the wetted walls.

Instead of the restored walls achieving a maximum racking load greater than that of the wet wall, they fail due to the sheathing buckling off the timber frame, as shown in Figure 5-14. This explains the slightly lower strength compared to that of the wet walls and the lower than predicted racking strengths. For all calculated mechanical properties, the variation of the condition 3 specimens is far higher than for the other conditions tested. Ultimate strength for example, has a CoV of 10%, which is double that for the control walls. This variation in the mechanical properties is caused by the out of plane buckling failure, as well as other flood induced effects such as swelling and shrinkage of framing joints. The buckling also causes the walls to fail in a mode not considered by the design codes or by the theoretical model on which they are based. The buckling failure is a sudden failure mode and is difficult to predict.

The wet walls do not exhibit the same out of plane failure due to the fact they are saturated with water. The wetted walls, condition 2, have the same curvature in the sheathing as the condition 3 walls however, they do not fail out of plane. Rather, the nails rip out of the OSB sheathing. This is because the wetting of the sheathing causes the OSB to soften significantly, reducing its embedment strength [82]. This can be seen in the results of Chapter 4 where the wetted specimens had a mean ultimate strength, F_u, 44% weaker than the control specimen strength. This compromised sheathing board is unable to transmit the buckling forces across its surface. Because it is softened so significantly, the board simply rips at the location of the greatest differential displacement between the sheathing and framing as the wall is loaded. Figure 5-22 illustrates this ripping of the board past the nail fixing it to the timber. The dried sheathing in condition 3 is however, stiff enough to transmit the buckling forces across its surface, hence it ultimately fails by buckling.

Implications

These results have significant implications with respect to the flood resilience of platform timber frame. Following flooding and subsequent restoration, a permanent loss of mechanical properties is to be expected. More significantly, a change in the failure mode is also possible. As a result of wetting and drying, the walls exhibit significant out of plane behaviour during loading. This out of plane bending reduces the strength of the walls to less than would be expected after drying. Importantly this behaviour is not accounted for by current design codes or theoretical models. The check for sheathing buckling resistance in Eurocode 5 and PD 6693-1 given in Eqn. 6.1 does not give any indication that this failure mode will occur. These checks would suggest that the walls will still have adequate buckling resistance but, this research shows that, following flooding there is a danger that timber shear walls could fail at a reduced strength due to this buckling behaviour.

Chapter 7

Discussion

The literature review in Chapter 2 demonstrated the lack of existing research into flooding on timber frame. Based on this research gap, a series of tests were performed in order to categorise the response of timber frame shear walls to flooding. The results of these experiments, presented in Chapters 4 and 5, provide insight into the behaviour of timber shear walls during and after flooding.

Two aims for the project were given in Chapter 3:

1. To identify an optimum drying method for timber frame structures,
2. Assess the effect of flooding on the structural performance and mechanical properties of timber frame structures.

The tests in Chapter 4 were primarily focused on identifying an optimised drying environment. Those in Chapter 5 focused on the structural performance of shear walls during and after flooding. The application of these results to each of the aims are explored in this chapter, as are the implications that the results have with respect to the overall flood resilience of timber frame.

It was noted by Lamond et al. [91] that new guidance regarding the repair of flooded structures would be welcomed. The new guidance recommended should be universal, easily accessed and address gaps in the existing guidance. As will seen in the following sections, the results of this research project can contribute significantly to such guidance by helping, in part, to address the knowledge gap in current documentation.

7.1 Optimisation of drying

Identifying an optimised drying condition was achieved in Chapter 4. This is important as this is the first study that has attempted to match drying conditions to building type. Mapping these two criterion is an issue that has been known about, but not researched, for over a decade. In this study, instead of studying drying time, the mechanical properties of the connection specimens tested were used to indicate drying efficacy. In Chapter 2 it was seen that flooding was likely to reduce the mechanical properties of the individual components of a timber frame structure and that the reductions could be permanent. It was also shown that the drying process itself could cause deterioration in the timber if managed incorrectly. Given these potential sources of damage, rather than focusing on the speed of drying, it was decided that maximising the return of mechanical properties after flood is a more important criteria than focusing simply on how long a structure takes to dry. Measuring drying time accurately is also challenging as the boundary conditions in a real structure during drying differ from those achievable in an experimental setup.

It is clear that being flooded causes damage to the structure and that one method by which this can be mitigated is through managing the drying environment employed. Employing the optimum drying environment and monitoring the structure until it has a moisture content of less than 20% ensures that the damage due to drying is minimised. This enables the maximum recovery of the mechanical properties. The time taken to dry may not the shortest possible however, the drying environment will not contribute to further deterioration in the mechanical properties.

7.1.1 Connection tests

Experimental results from Chapter 4 showed that, within certain limits, decreasing relative humidity and increasing temperature caused improved strength recovery in the connections. For maximising the recovered strength of the connections, an environment of 40% RH and 38 ^{0}C was found to optimum.

Using this environment, the highest post-drying ultimate strength, F_u, and yield strength, F_y, were observed. It was also observed that relative humidity was more influential in the drying process than the temperature. These results are consistent with work discussed in Chapter 2 where it was shown that excessive heat or excessively low humidity can cause damage to timber products during drying [58, 64, 67]. When RH was too high, damp patches were found in the connection specimens and when RH was less than 40%, the specimens were slightly weakened, see Chapter 4. A relative humidity of 40% is within the optimum range suggested by [66], see Table 2.3.

The results also show that the process of wetting and drying causes permanent losses in the mechanical properties of the specimens. The permanent losses were observed in the OSB, not the timber. As a result, the OSB properties govern the strength of the connections after drying. This is in agreement with the component material tests discussed in Section 2.6, where it was seen that timber recovered to its original embedment strength but OSB did not. The permanent strength loss in the connection is due to the process of OSB swelling as it absorbs flood water. As reported in existing literature, the swelling causes the adhesive bonds between layers of the OSB to rupture, permanently reducing the mechanical properties [80, 81].

Trapped moisture

One observation of particular note was the trapped moisture observed in some specimens. As shown in Figure 4-12, areas of elevated moisture were still present in the the timber element of some connection specimens. The surface of the timber is dry however, the central section remains at over 20% MC. In the case of the specimen shown in Figure 4-12, surface MC readings had indicated that the MC was below 20%. The area of elevated MC was only visible after destructive disassembly of the specimen. PAS 64 [68] recommends drilling into the frame and using longer, insulated pins to survey moisture content in order to identity this type of trapped moisture. This procedure was not followed for these tests as it may have affected the specimen mechanical properties through excess material removal.

The discovery of trapped areas of elevated moisture highlights the importance of correctly surveying and monitoring buildings as they dry. It is very easy to miss such areas in a frame which, if not identified and dried, could lead to serious long term problems with rot and mould growth as well as a potential reduction in mechanical properties.

7.2 Structural behaviour of shear walls

The connection tests performed in Chapter 4 confirmed that there is a permanent reduction in mechanical properties. These results were in agreement with existing data for component materials, as discussed in Chapter 2. Although the connection tests indicate likely behaviour in terms of strength, they do not accurately predict the full behaviour of the shear wall. Certain properties such as stiffness or out of plane behaviour cannot be inferred for shear walls from the connection model. As such, it is necessary to perform tests on full shear wall assemblies.

Making use of the flood tank at the University of Bath's newly constructed, specialist reseal centre, "The HIVE", enabled this type of testing to be achieved more easily than would otherwise have been possible. Shear walls were load tested in three states to allow comparison of behaviour before flooding, during flooding and after recovery from flooding by drying. The drying environment chosen was that which had been identified as optimum in Chapter 4; 40% RH and 38 ^{0}C. Load testing was performed according to the BS 594 standard for racking tests [122]. Because of overhead restrictions in the available drying chamber, the shear wall height was reduced. As such, some modifications were made to the standard test procedure to account for the reduced height of the walls. In addition, more displacement sensors were placed along the wall than are required by the test standard. Four mechanical properties were derived from the data; ultimate strength, F_u, yield strength, F_y, initial stiffness, k and ductility, μ. These properties were used in conjunction with visual observations made during the tests, to compare walls at different stages of flooding.

As expected, simulated flooding and drying resulted in a permanent loss of shear wall mechanical properties. F_u, F_y, k and μ were all lower in the walls tested when wet compared to the control walls. The ductility class dropped from "highly ductile" to "moderately ductile". The same was true for the walls tested after being dried. When compared to the control walls, all mechanical properties were reduced.

The comparison of the wet walls to the restored walls was surprising. The mean values of F_u and F_y were greater in the wet walls than in the restored walls however, the stiffness of the restored walls was greater. Based on component material tests and the connection test results presented in Chapter 4, it might have been expected that the restored walls, whilst not fully recovering to their original, pre flood performance, would outperform the walls that were tested when wet. The restored connection specimens presented in Chapter 4 were generally stronger than those tested when wetted for five days. Work discussed in Chapter 2 also showed that the embedment strength of the OSB and timber are greater after drying than when wet. Since the connection strength governs wall strength, it is expected that the restored walls would be stronger than the wet walls.

7.2.1 OSB and out of plane action

As discussed in Section 5.3.2 and Section 6.5, the wall sheathing was observed to buckle due to swelling. As the OSB sheathing absorbs water during the simulated flooding, it swells. For the connection specimens, this water absorption resulted in simple thickness swelling of the OSB. In the shear walls however, the swelling is restrained by the nail line fixing the OSB to the timber frame. This restraint causes the sheathing board to curve as it swells due to water absorption. When the sheathing dries, the curvature remains, ultimately leading to the buckling failure. The sheathing bends when loaded; buckling away from the frame. The swelling of the OSB also causes rupture of the inter-layer adhesive, permanently reducing the mechanical properties of the sheet. As such, the board is compromised with respect to both geometry and mechanical properties.

Failure due to buckling of the sheathing is not accounted for in the design codes. The result of the buckling failure combined with strength loss due to swelling and inter-layer rupture, is that the restored walls have a mean ultimate strength less than that of the control specimens by approximately 25%. The wet walls had a mean ultimate strength that was less than the control walls by approximately 20%. The buckling of the sheathing significantly impacts on the strength of the restored walls. The buckling failure is also reflected in the high variation (CoV) in mechanical properties observed in the restored specimens.

As noted in Chapter 5, not all of the nailed connections between sheathing and timber in the test walls were perfect. Some nails were misfired, affecting the strength of the walls. This misfiring of nails was used to explain in part the poor fit between the Källsner and Girhammar and PD 6693-1 models and the experimental data.

7.3 Implications for recovery after flood

The results presented in Chapters 4 and 5 have significant implications for the drying and restoration of flooded buildings. The first aspect to examine is the question of how to dry timber frame. Implementing the optimised drying results in real structures that have flooded simply requires deploying a mechanical drying system that is able to maintain the appropriate temperatures and relative humidities. If the optimum temperature or RH cannot be maintained perfectly, an attempt to lower RH should be made and the temperature gently increased. As discussed in Chapter 2, Section 2.5.1, setting relative humidity too low should be avoided as it can damage the frame by causing the OSB and timber to dry too quickly. Excessively high temperatures should be avoided for the same reason. It is also important to correctly survey the timber frame during drying to ensure that no moisture remains trapped. If present and not detected, its could lead to severe problems with rot or mould growth.

In Chapter 2 it was mentioned that the usual repair process for timber frame is to strip out internal plasterboard and sheathing and to then remove insulation from the inside of the wall. The room is then dried and the interior restored to its original finish. Clearly it is impractical to remove any sheathing that remains on the exterior face of the wall. This sheathing cannot be removed easily so is left in place and dried. An important question to answer is therefore, how much of the remaining sheathing strength can be safely utilised in the repaired structure?

The layer of sheathing left in place will be subject to the effects of swelling induced curvature seen in Chapter 5. This is likely to lead to to buckling failure when the wall is loaded. Relying on its entire ultimate strength is not safe however, entirely discounting its contribution to racking resistance is wasteful. The experimental results in Chapter 5 showed that, despite the buckling failure, the restored walls maintained approximately 75% of their pre-flood ultimate strength. Reinstating the structure requires that it still be able to resist the design loads. Clearly, re-sheathing the internal face of the wall generates a certain amount of resistance to imposed loads. The external face with the damaged OSB still contributes to the wall performance however, it is at risk of buckling failure so cannot be relied upon up to its ultimate limit state. The contribution to resistance of the damaged sheathing must be limited somehow.

It is also worthwhile considering some of the risks to the timber frame during the reinstatement process. For example, if damaged internal sheathing is stripped out for drying and only the external sheathing remains, the wall loses lateral resistance capacity. During drying, the wet OSB has reduced embedment strength and is at risk of failure in the wetted zone of the wall. Once dry, the same OSB is at risk of buckling failure. The reduction in strength as a result of reduced embedment strength in the sheathing when wet and permanent loss of mechanical properties of the sheathing when dried, in combination with the loss of lateral resistance as a result of internal strip out, should be carefully considered when planning repairs. Clearly the specifics depend on the individual structure and details of the flood however, it may be worthwhile considering, for example, repair of a single room at a time in order to mitigate the risk of multiple sources of reduction in capacity.

7.4 Design procedure for flood repair

In this section, a procedure for deigning the repair of flooded timber shear wall buildings is proposed. It is based on the data presented in Chapter 5 and borrows terminology and approach from the PD 6693-1 method. PD 6693-1 is referenced as it is the current UK design methodology.

7.4.1 Design process

In terms of design process, the proposed procedure would be very similar to that already given in PD 6693-1. PD 6693-1 gives a factor, K_{comb}, to be used when combining more than one sheet of sheathing in a wall (see Table 8, Section 21.5.2 of PD6693) [41]. The factor K_{comb} modifies the design shear capacity of the nail fasteners that form the connection between the sheathing and timber. For a single layer of sheathing, $K_{comb} = 1$. In a wall where a second layer of the same sheathing is applied to the opposite side of the wall using the same nailing density, $K_{comb} = 0.75$ for the connection strength of the second sheathing layer. As discussed in Chapter 2, the strength provided by additional sheathing is additive however, this is modified to be conservative by design codes and having $K_{comb} = 0.75$ achieves this. Where a wall is sheathed with a second sheathing layer on the same side and fixed on top of the first, $K_{comb} = 0.5$ for the connection strength of the second sheathing layer.

In the case of a wall being restored after flooding, it is proposed that the **damaged sheathing** remain in place and have a strength reduction factor, K_{flood}, applied to it. The new internal layer of sheathing fixed after the structure is dried should have no reduction factor. That is, $K_{comb} = 1$. The wall will then have contribution to strength from two sheathing layers; the new undamaged layer which is fully utilised and the old, damaged layer utilised at a reduced capacity. The question that arises is therefore, what remaining capacity of the damaged OSB can be utilised safely?

The value of K_{flood} must reflect the damage to the sheathing and the risk of buckling and should be based on the expected 95$^{\text{th}}$ percentile reduction strength due to flooding. That is, no more than 5% of shear walls should experience a greater loss in strength. Since shear walls are designed using the plastic capacity of the nailed connection, it is the ultimate strength of the wall that is of interest. In order to capture the risk of buckling, the reduction factor is based on the shear wall data from Chapter 5, where the restored walls failed due to sheathing buckling.

7.4.2 Statistical Model

A statistical model is used to predict the expected reduction in strength that only 5% of walls should experience greater reduction in strength than. that is, only 5% of walls will exceed this reduction in strength. For the purposes of this model it is assumed that the distribution of shear wall strengths is normal. Note that the model is based on a small data set and, increasing the number of specimens included would increase its accuracy See also Section 7.5.1.

Mean strength

For the control walls, the mean ultimate strength, $\mathrm{F_u}$, was 18.2 kN, with a standard deviation, $\sigma = 0.93$. The restored walls had a mean $\mathrm{F_u}$ of 13.8 kN and standard deviation, σ=1.37. Assuming both are normally distributed, the strength distributions of each condition can be expressed as:

$$F_{u,\,control} \sim \mathcal{N}(18.2, 0.93) \tag{7.1}$$

and

$$F_{u,\,restored} \sim \mathcal{N}(13.8, 1.37). \tag{7.2}$$

These distributions are illustrated in Figure 7-1.

The mean reduction in strength is simply the difference between the two means. Here the difference between the means is expressed as a percentage of the control specimen mean:

$$\Delta_{mean,\%} = \frac{\overline{F_{u,\,Control}} - \overline{F_{u,\,Restored}}}{\overline{F_{u,\,Control}}} \times 100 \tag{7.3}$$

where $\overline{F_{u,\,\mathbf{condition}}}$ is the mean ultimate strength of a given condition. In this case the percentage difference in mean is as follows:

$$\Delta_{mean,\%} = \frac{18.2 - 13.8}{18.2} \times 100 = 24\%. \tag{7.4}$$

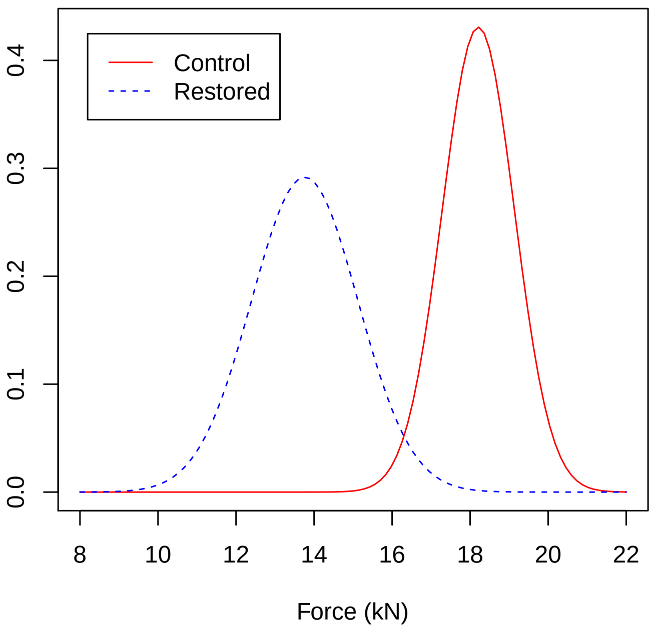


Figure 7-1: Normal distributions of shear wall strength for control and restored conditions. The solid line (red) represents the control group, the dashed line (blue) represents the restored group.

The mean loss in strength for restored walls is 24%, relative to the control condition.

Variance

Calculating the variance of the difference between the distributions for two conditions as given in Equations 7.1 and 7.2 is more challenging.

The calculation of the variance (var), σ^2, can be approximated using the Delta Method, where $E[X]$ and $E[Y]$ are the expected values, or means, of distributions X and Y.

The variance of $\frac{X-Y}{X}$ is calculated as follows:

$$var\left(\frac{X-Y}{X}\right) = \frac{E[Y]^2}{E[X]^4}var(X) + \frac{1}{E[X]^2}var(Y) - 2cov(X,Y)\frac{E[Y]}{E[X]^3} \tag{7.5}$$

where the covariance of X and Y, $cov(X,Y)$, is 1.132.

Setting $X = \overline{F_{u\,control}}$ and $Y = \overline{F_{u\,restored}}$ gives variance, σ^2 equal to 0.001954709. The standard deviation, σ, is the square root of the variance and is calculated as approximately 0.044.

Modelled loss of strength

Having calculated the mean and the variance, a distribution can be generated that represents the expected loss in strength. Assuming the expected loss in strength is again normally distributed, the percentage strength loss of restored walls with respect to their original condition can be expressed as:

$$Loss_{(\%)} \sim \mathcal{N}(0.24, 0.044) \tag{7.6}$$

This distribution is illustrated in Figure 7-2, page 177.

From this distribution, the 95$^{\text{th}}$ percentile value can be calculated. This is the percentage loss in strength that only 5% of walls would exceed. Note that the distribution is a percentage reduction in strength with respect to the control condition.

The calculated value for the 95$^{\text{th}}$ percentile is 0.3172. This is equivalent to an approximate strength reduction of 32%. Based on these calculations, the damaged sheathing should have a correction factor, $K_{flood} = 0.32$ applied to it. At this level, only 5% of all all walls will experience greater loss of strength due to wetting, drying and buckling effects.

7.4.3 Summary

A statistical model as used to determine the value of K_{flood} such that only 5% of structures will exceed the expected strength loss. The approach was designed to be consistent with the terminology of the current UK design method, PD 6693-1. This design approach allows the remaining strength of the existing sheathing to be utilised, despite the damage it suffers due to the flooding. Although damaged and susceptible to buckling, the proposed design process ensures that the OSB is unlikely to buckle in service within the design envelope.

Assuming the wall is re-sheathed internally, this approach provides racking resistance from two sources; the new sheathing layer and contribution from the old, flood damaged layer. If these two layers do not provide adequate design resistance then there are two approaches that can be taken:

1. Add an additional layer of new, internal sheathing with $K_{comb} = 0.5$ to provide additional resistance.
2. Use a thicker sheathing board in the new sheathing layer to increase the nailed connection capacity.

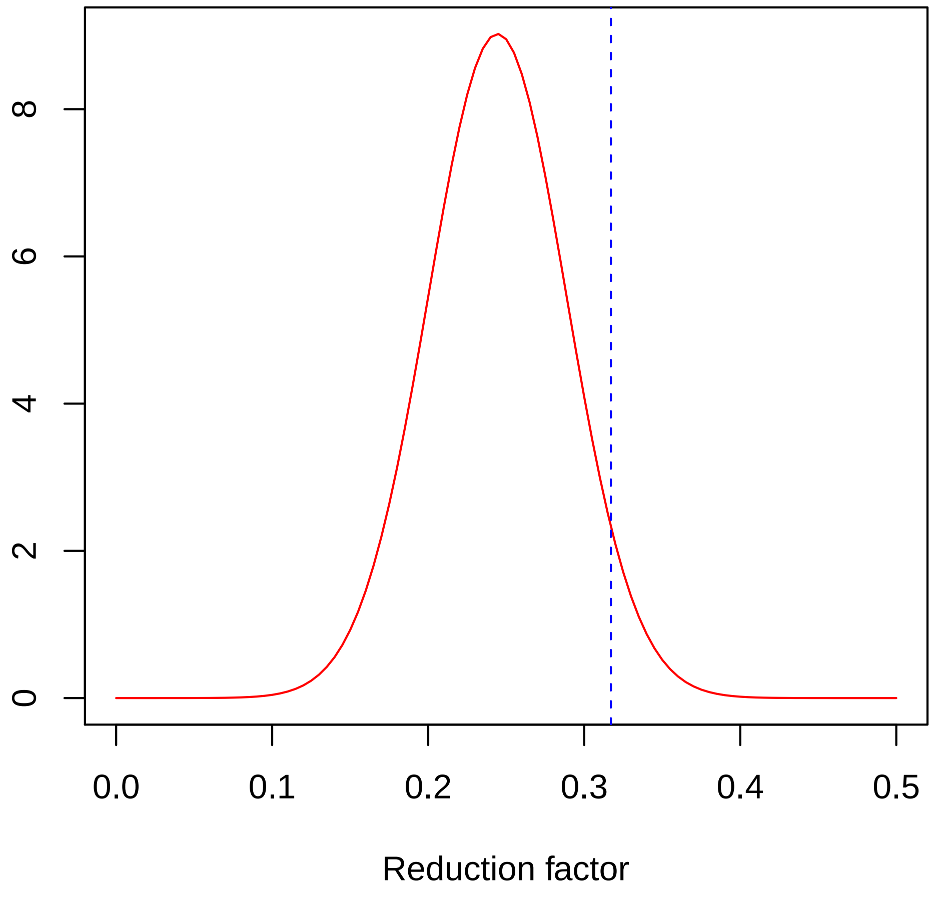


Figure 7-2: Normal distribution of the expected percentage strength reduction of restored walls with respect to control specimens. The vertical line (dashed, blue)indicates the 95^{th} percentile value of percentage reduction; 0.3172 or approximately 32%. Only 5% of walls will experience a reduction in strength of more than 32%.

7.5 Study limitations and restrictions

The investigation reported in this thesis has limitations as well as some restrictions and these are discussed and addressed in this section.

7.5.1 Limitations

There are a small number of limitations that restrict the scope of the work presented here. Some possible methods by which these limitations could be addressed are presented in Section 7.5.3. The study limitations are as follows:

1. Small sample size during shear wall tests.

2. Moisture content of specimens varies.

3. A single flood depth and duration of were investigated.

4. Investigation limited to a single wall construction type.

5. Effect of contaminated water not studied.

6. Water temperature (freeze/thaw) not investigated.

1. Sample size

This thesis investigated only three wall conditions, with only three specimens per condition. Testing greater numbers of walls per condition would generate a more comprehensive data set from which to draw conclusions. Earlier in this chapter a proposed method for designing repairs was proposed and a characteristic value of strength loss was calculated in Section 7.4. The distributions used to calculate the characteristic loss percentage are based on only three specimens per condition. A small number of samples results in larger variations (CoV) between the results. A greater number of specimens per condition would make the results of the calculations more reliable.

2. Varied moisture content

The moisture content of each specimen tested varied. The was due to the moisture content criteria chosen for the tests. Specimens were tested as soon as a MC of ¡ 20% was achieved, rather than at a specifically defined MC. This replicated the target MC of a proprty being dried after flooding. The variation in MC between specimens will result in slight differences in the material properties of each specimen tested. As such, some of the reduction in strength observed in the connection tests in Chapter 4 is attributable to the MC variation. This variation in MC is also responsible for some of the variation observed between specimens.

3. Flood depth

Only one flood depth was investigated. From these results it is not possible to quantify the relationship between flood depth and the extent of loss of mechanical properties of the wall. It would be reasonable to assume that shallower flood depths would result in less damage and greater flood depths in more damage however, this is not clear without further testing.

4. Construction type

The walls tested were of one particular construction type, OSB cladding on a timber frame. The effect of different sheathing materials or OSB thickness is not addressed by the investigation.

5. Water quality

Only fresh water was used to flood walls during testing. This was a necessary limitation as handling contaminated flood water was not practical on the scale required. This means that the effect of biological contaminants on the shear wall cannot be determined. There are unlikely to be major structural ramifications because of biological contaminants however, the health of occupants can be severely impacted.

7.5.2 Restrictions

There were some restrictions to the experimental study imposed by the equipment or facilities available at the time the research was conducted. Potential methods to address these restrictions are given in Section 7.5.3.

A restriction in the study was the wall height that could be tested. Because of overhead restrictions in the drying chamber used, walls were limited to 1.8 m in height. The drying chamber used also impacted the type of drying it was possible to simulate. In Chapter 2, Section 2.7.1, the difficulty of simulating drying accurately was discussed (see also Figure 2-13 on page 61). Because of the equipment available during this study, walls were dried evenly on all sides. This is not an accurate model of real drying boundary conditions and as such, drying time cannot be accurately determined.

7.5.3 Addressing study limitations and restrictions

The limitations given in Section 7.5.1 are mostly simple to address. Future experimental studies should aim to test more specimens and to include more wall construction types; plywood sheathing, thicker OSB etc... It would also be beneficial to test multiple flood depths. It is likely that the buckling of the sheathing will be less severe with shallower flood depths. Shallower flood would also result in less of the board having reduced mechanical properties. If this were the case then it may be appropriate to leave the dried OSB in place, if the structural performance is adequate. Understanding the relationship between flood depth and loss of strength would be beneficial to those recovering from flood as it has the potential to reduce the cost of recovery.

The most difficult limitation to address is that of contaminated water. Handling contaminated flood water safely in the quantities needed for simulating flooding is not simple. It may be better to investigate the effects of biological contaminants on shear walls at a smaller scale to help address this difficulty.

The height restrictions mentioned in Section 7.5.2 require a larger drying chamber than was available during this project. If such a facility was available it would be possible to test taller walls and those produced commercially. This introduces the advantage of industrial quality control procedures and the wall design would reflect current manufacturing practice with respect to vapour barriers, insulation etc... Taller walls are more representative of real use cases and the use of commercially produced walls would also help to reduce the problem of misfired nails.

In the experiments performed during this investigation, drying time was not monitored. Instead, recovery of mechanical properties after drying was used to assess drying efficacy. This is due to the difficulty in accurately simulating real drying conditions in the lab. Drying time is however, an important issue for many flood victims. Differences between public expectations and the reality regarding the time taken to dry properties are often the source of conflict, leading to a lack of satisfaction on the part of the flood victim. As such, the issue of drying times should be addressed. There are two possible approaches to this problem, both of which should be explored:

1. Better educate the public as to the likely length of time drying will take.
2. Perform more research designed to assess the time taken to dry structures after flood, including under different drying conditions.

Addressing the first point requires current knowledge to be better disseminated. Existing estimates for drying times suggest that more than six months to complete the process is not uncommon, despite expectations to the contrary [16, 91, 97]. Making the public more aware of realistic time scales for the flood recovery process would help alleviate some of the confusion around drying time.

Addressing the second point regarding more research is complex. Recreating accurate boundary conditions for drying is challenging, see Chapter 2, Section 2.7. Room size, layout of walls, location of windows, location of drying equipment etc... are all influencing variables. One approach would be to flood full size test structures, similar to the experiments conducted in [98]. This is understandably expensive and requires a suitable site. Another approach would be to monitor the drying behaviour of structures after actual flood events. This would require identification of suitable properties and permission of the occupants. Using real or full size test structures makes load testing after the flooding and drying extremely difficult. Such an approach would therefore likely be limited to an investigation of drying time only. No information on the mechanical properties of the structure could be easily captured. Insurance companies may already hold data related to drying method and drying times however, if this is the case, none were forthcoming during this course of the current investigation.

7.6 Future Work

Possible avenues for further work that emerged during the course of the current research are explored in this section.

7.6.1 Future work

The most valuable further work based on this project would be further testing of flooded shear walls. Testing full sized walls, greater numbers of walls and testing walls flooded to different depths would enable a more accurate picture of the flood depth/damage relationship to be developed. A larger sample would improve the reliability of the statistical model presented in Section 7.4.2.

7.6.2 Different sheathing materials

Another obvious area for study is the materials used to sheath a shear wall. In these tests, 9mm OSB/3 sheathing was used. Investigating the effect of thicker OSB sheathing would be worthwhile. Using thicker OSB results in a greater timber to sheathing connection strength for undamaged walls. If thicker board is less prone to the effects of flooding; inter-layer rupture, swelling and the resultant buckling, then it could offer a more flood resilient option for sheathing structures. Without testing however, there is no guarantee that thicker OSB would be any more effective in flood than the 9 mm thick OSB. For flood prone areas, the use of OSB/4 may also be worth considering.

OSB is the most common sheathing material used in shear walls in the UK however, it is not the only one. It is reported that Plywood can be a more resilient than OSB when exposed to elevated elevated moisture contents however, its use in as sheathing in a wall panel subject to flood has not been tested. Other novel materials such as acetylated sheathing products would also be interesting to test.

It is important to test different materials as they have the potential to change the drying dynamics of the structure, especially acetylated products. The study by Aglan [99] shows how influential seemingly minor changes in construction detail can be on the drying of a structure. Construction materials and details that adversely affect a structures ability to be dried should be avoided.

7.6.3 Repair procedure

It is important to test walls that have been repaired according to the procedure detailed in Section 7.4. It is not immediately clear how timber frame shear walls will perform when sheathed in a mix of damaged and undamaged OSB sheathing. The assumption is that is unlikely there will be any adverse interactions as a result of the approach however, without testing this is not clear. It is possible that the damaged sheathing will fail and the repair sheathing layer will continue to provide resistance until its failure. To determine exactly how this occurs and how the wall will resist load will require experimentation on repaired walls.

7.6.4 Monitoring out-of-plane behaviour

The buckling observed in the restored walls was unexpected. Nothing in the literature or from prior tests suggested this type of failure would occur and as such, the tests were not set up to monitor it in detail. The phenomenon was recorded via photographs and experimenter observations only. Future experimental work concerning flooding and timber frame should take care to instrument the specimens in order to better record the buckling of the sheets. This could be achieved through placement of transducers on the surface of the sheathing in the out of plane direction, or perhaps via the use of two dimension digital image correlation (2D DIC). Using 2D DIC would allow the sheathing curvature and out of plane actions to be recorded automatically. The DIC approach is relatively simple as the OSB panel is already sufficiently textured to work with most DIC algorithms [128].

7.6.5 Multiple flood events

The final area of further investigation suggested is into the effect of repeated flooding. The data in this research are for freshly constructed walls subject to flooding once that are then load tested. It is possible however, that a structure will flood more than once. For many victims, a particular flood may not be their first experience of flooding. Some homes can even flood more than once in the same floods, as happened to some home owners in 2007, 2012 and 2014. In such cases, structures will be dried on multiple occasions. It is not clear what effect this will have on the long term performance of a timber frame structure. It has already been established that flooding and drying causes permanent reduction in the mechanical properties of OSB, with the timber recovering its original properties well. There is however, no data for multiple flood events. It is feasible that OSB will continue to lose capacity after each repeat flood. The effect repeated flooding has on timber is entirely unknown and is certainly worth of further study.

Summary of further work

Suggestions for further work are summarised below. This list is by no means exhaustive but serves as a good starting point for future research projects.

- Conduct more load tests on more sample walls.
- Use sample walls supplied by a commercial timber frame builder.
- Use full height walls.
- Investigate the effect of multiple flood depths.
- Attempt to contact insurers in order to perform a desk study into drying methods and drying time of timber frame.
- Attempt to study drying time by simulating drying conditions more accurately.
- Study the effect of different sheathing materials and OSB thickness on the drying and structural behaviour.

- Generate characteristic connection strength data for flooded and restored structures via an extensive program of connection testing.
- Perform a more detailed investigation into the buckling effects observed;
  - Use 2D DIC to track out of plane movements
  - Use strategically located LVDTs to track out of plane sheathing movements.
- Load test repaired walls.
- Test walls subject to repeat flooding.

7.7 Chapter summary

At the beginning of this chapter the project aims were restated. The way in which experimental data was used to address these aims was then explored. Studying the results of Chapters 4 and 5 enabled a proposed design methodology for repair of timber frame to be developed. The approach utilises the residual strength of wetted OSB sheathing whilst ensuring buckling is not the dominant failure mode. This approach allows for a more efficient repair process than simply discounting the contribution of the damaged sheathing.

The chapter concluded with a brief discussion of limitations in the research performed and provided suggestions for further work. The are a number of new areas of research worthwhile exploring based on the results of this project.

Chapter 8

Conclusions

Prior to this project there was a serious shortage of experimental investigation into the effects of flooding on timber frame structures. The literature showed an inadequate amount of research into flooding of timber frame structures and, what research did exist, did not address critical concerns such as changes to mechanical properties or structural behaviour of the timber frame. This scarcity of research has led to a situation where guidance documents for restoration after flood are generally lacking in detail. No precise recommendations as to the best approach to drying after flooding are given. In addition, no studies explore the loss in capacity of timber frame or its change in behaviour due to flood. This has led to timber frame construction both being recommended as a flood resilient solution and opposed as an appropriate construction choice, without any supporting evidence. The performance of timber frame during and after flood was not known.

8.1 Research contribution

This project presents a systematic study of the effect that flooding has on platform timber frame structures. It gives results regarding structural behaviour of shear wall elements during and after flooding as well as addressing optimised drying solutions. As a result of the work contained in this thesis, better, more informed decisions on drying and restoration of timber frame can be made from a basis of sound experimental evidence. This thesis has characterised the response of existing timber frame construction to the effect of flood. Given the scarcity of data on this subject, identifying the response of the existing timber frame structural paradigm to flood was deemed more critical than attempting to improve its resilience. It is not possible to improve the flood resilience of the structural system before understanding how it currently responds to flooding.

8.2 Research aims

In Chapter 3 two research aims were given:

1. To identify an optimum drying method for timber frame structures,
2. Assess the effect of flooding on the structural performance and mechanical properties of timber frame structures.

The results of the project have enabled these aims to be addressed. The connection tests performed in Chapter 4 demonstrated that it is possible to optimise drying of timber frame to prevent further structural damage and ensure a maximum return to pre-flood mechanical property values. The optimum conditions identified are in agreement with general drying guidance for lumber (see Chapter 2). Relative humidity is the most important variable to control. Reductions in RH improve the recovery of mechanical properties. Increasing temperature is effective in improving drying outcomes but only if done whist controlling RH.

8.3 Shear wall behaviour

In Chapter 5, load testing timber shear walls at different stages of the flooding and drying process confirmed expected performance and revealed changes in behaviour that had not been previously observed. As expected, load carrying capacity of shear walls was reduced when wetted due flooding. After drying, the walls did not recover to their full capacity; the losses in capacity observed after flooding and drying are permanent. The stiffness of the walls decreased due to flooding and was somewhat recoverable by drying however, not fully. Both wet walls and those recovered by drying were observed to have dropped a ductility class compared to the control walls. These results fit with observations from previous material and connection tests, see Chapter 2 and Chapter 4. Although a reduction in strength and stiffness is expected due to flooding, this project is the first the author is aware of where this behaviour has been demonstrated experimentally in a full structural system.

The performance and behaviour of the shear walls after drying were unexpected. The restored shear walls exhibited a lower ultimate strength than the wet walls. This was as a result of sheathing buckling when load tested. The buckling is a direct result of flooding. When wetted, the OSB sheathing expands however, it is restrained by the nail line that fixes it to the frame. The restraint causes the board to curve rather than simply expand when it swells due to moisture absorption. This curvature remains when the sheathing is dry and its presence ensures the sheets fail in buckling rather than via the nailed tearing out of the OSB as displacement increases. This curvature of the sheet and subsequent buckling has not been reported before.

8.4 Repair

These are important findings as they show that the structural behaviour of the shear wall changes as a direct consequence of flooding. They also have implications for the repair of the structure. Commonly timber frame is "stripped out" after flooding. Internal plasterboard, sheathing and insulation are removed to facilitate drying. The structure is then reinstated with new insulation, internal sheathing and internal finishes. The external sheathing, the layer facing the wall cavity, must be left in place. After a flood, a timber frame wall will likely contain a layer of sheathing that has been damaged but is still in place. No guidance specifically addresses repair beyond instructing home owners to "*repair*" and "*reinstate*" their homes to their original condition. In Chapter 7, a new design approach for repairing timber frame after flood was presented. Rather than taking an overly conservative approach where the contribution to lateral resistance of the damaged sheathing is ignored entirely, the new method proposed attempts to utilise the remaining strength safely. Ignoring the damaged sheathing is overly conservative however, care must be taken to ensure that the design capacity does not rely on OSB that is likely to buckle. As such, it is suggested that a eduction factor $K_{flood} = 0.32$ be applied to the damaged sheathing. This allows the design strength of the wall after flood to include a safe contribution from the damaged OSB.

8.5 Summary

The results of this thesis show that timber frame is flood resilient, assuming the correct drying and repair process is followed. The fact that timber frame requires drying and re-sheathing is not necessarily a limit to its flood resilience. All structures subjected to flooding will require some form of repair or reinstatement before occupants can move back in, and timber frame is no different in this regard. It is possible to go further and argue that flooding is not a structural issue where platform timber frame is concerned. As long as the correct drying and reinstatement procedures are followed, the structure is not at risk of disproportionate collapse; test walls showed a loss in ultimate racking capacity of 20% and 25% for the wet and restored specimens respectively. Flooding of timber frame is, arguably, an environmental and occupational problem rather than one of structural risk, assuming correct recovery procedures are followed. Timber frame has the capacity to be restored and repaired to sufficient design strength thus, drying time, mould growth and indoor air quality become the critical issues due to flood, not collapse.

Having identified and addressed the insufficiency of research into timber frame and flooding, this research has potential for significant impact. As noted by Lamond et al. [91], there is a demand for a new universal guidance document that addresses the gaps in current documentation. This research can clearly contribute to such a publication through new information on optimised drying conditions and structural behaviour. The results presented in this thesis move forward the understanding of timber frame and its response to flooding. These results and new insights will be of great benefit to those in timber frame structures who become victims of flood.

Although the exact location, severity and timing of floods are difficult to predict, they are a known risk. They are also a risk that is within the engineers scope to design for. The UK faces a continued risk of flooding and engineers should consider as many elements of flood risk as possible in their designs, including repairs to timber frame structures. The results of this thesis help enable that ability.

This project has characterised the response of existing platform timber frame to flooding. Within the existing construction paradigm it has been shown that timber frame construction is flood resilient and that the repair of timber frame after flooding has occurred can be designed in a relatively simple fashion.

References

[1] The United Nations Office for Disaster Risk Reduction (UNISDR). Number of Climate-related Disaters Around the World (1980-2011) , 2012, Available at: `http://www.unisdr.org/we/inform/disaster-statistics`, *Last accessed:* 22/04/2015, *Infographic by the UNISDR on the number of worldwide climate related disasters.*

[2] Sir Amyas Morse. Flood risk management in England, 2011, Report, National Audit Office.

[3] Sir Micheal Pitt. The Pitt Review: Learning lessons from the 2007 floods, 2008, Independent Report, HM Government.

[4] BBC. Flood water remains 'up to 13ft' on somerset levels, 2014, Available at: `http://www.bbc.co.uk/news/science-environment-26414428`, *Last accessed:* 21/05/2015, BBC Radio 4, Today Programe interview, BBC Online.

[5] IPCC, 2013: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Technical report, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2013.

[6] Sir Amyas Morse. Strategic flood risk management, 2014, Report, National Audit Office.

[7] Confederation of British Industry. Housing Britain: Building new homes for growth, 2014, Available at: `http://www.cbi.org.uk/media/2876609/homes-for-growth.pdf`,, *Last accessed:* 14/12/2014, Confederation of British Industry, CBI.

[8] Confederation of British Industry. Solid Foundations: Attracting institutional investment to homes built for rent, 2014, Available at: http://www.cbi.org.uk/media/2541021/cbi_housing_rpt_0114.pdf, *Last accessed:* 14/12/2014, Confederation of British Industry, CBI.

[9] Jesus M. Menendez, Kenneth Leitch, and Robert Hairstans. Sole plate fixing details for modern methods of timber construction. In Simon Aicher, H.-W. Reinhardt, and Harald Garrecht, editors, *Materials and Joints in Timber Structures Recent Developments of Technology*, volume 9 of *RILEM Bookseries*, pages 109–118. Springer Netherlands, 2014.

[10] Structural Timber Association. Market Report 2012, October 2013, Strucutral Timber Association.

[11] Oliver Bennet and Sarah Hartwell-Naguib. Parliamentary Archives, SN/SC/57555: Flood defence spending in England. Technical report, House of Commons Library, 2014.

[12] Annon. Improving the flood performance of new buildings. Flood resilient construction, 2007, Government, Department for Communities and Local and Defra, RIBA Publishing.

[13] Alistair Bradley, Wen-Shao Chang, and Richard Harris. The effect of drying on timber frame connections post flooding. *Construction Materials, Proceedings of the Insitiute of Civil Engineers*, 2015. http://www.icevirtuallibrary.com/content/article/10.1680/coma.14.00042.

[14] Oxford English Dictionary. “flood, n.”, Available at: http://www.oed.com/view/Entry/71808, *Last accessed:* 22/04/2015.

[15] Ilan Kelman and Robin Spence. An overview of flood actions on buildings. *Engineering Geology*, 73(3–4):297–309, 2004.

[16] David G Proverbs and Robby Soetanto. *Flood damaged property.* John Wiley & Sons, 2008.

[17] D. Guha-Sapir, R. Below, and Ph. Hoyois. EM-DAT: International Disaster Database, 2010, Online Database, Available at: http://www.emdat.be/, *Last accessed:* 22/04/2015.

[18] Environment Agency. Flooding in England: A National Assessment of Flood Risk, 2009, Report, Available at: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/292928/geho0609bqds-e-e.pdf, *Last accessed:* 01/02/2015.

[19] Schaller N. Results of "Weather@home 2014: the causes of the UK winter floods" project, Available at: http://www.climateprediction.net/weatherathome/weatherhome-2014/results/, *Last accessed:* 23/03/2015, *Part of a climate change research project utilising distributed computing resources. Results have been released on the project website and are awaiting publication in a peer reviewed journal.*

[20] Myles Allen. IPCC Media Briefing, March 2014, Press conference, Available at: http://client.cntv.at/EGU2014/?play=32. (Talk from 28 mins.), *Last accessed:* 23/03/2015, Myles Allen presents preliminary results of the "weather@home" study into the 2014 winter flooding.

[21] Anon. The Government's Response to Sir Michael Pitt's Review of the summer 2007 Floods. Final Progress Report, 2012, DEFRA.

[22] ABI. Flood Re explained, Feb 2015, Available at: https://www.abi.org.uk/Insurance-and-savings/Topics-and-issues/Flooding/Government-and-insurance-industry-flood-agreement/Flood-Re-explained, *Last accessed:* 22/03/2015, Association of British Insurers.

[23] Defra. A short guide to Flood Re, 2014, Report, Available at: https://consult.defra.gov.uk/flooding/floodreinsurancescheme/supporting_documents/A%20short%20guide%20to%20Flood%20Re.pdf, *Last accessed:* 22/03/2015, Defra.

[24] Daniel Johns. The practical implications of emerging trends, January 2015, Oral presentation, *Talk given by Daniel Johns, Head of Adaptation for the Committee on Climate Change at the* Flooding 2015 *conference in London*, Flooding 2015.

[25] Carrington D. Flood Re insurance scheme "needlessly expensive", Feb 2015, Available at: http://www.theguardian.com/environment/2015/

feb/05/flood-re-insurance-scheme-needlessly-expensive, *Last accessed:* 22/03/2015, Guardian Online.

[26] Harrabin R. Flood insurance scheme "wasteful", Feb 2015, Available at: http://www.bbc.co.uk/news/science-environment-31138997, *Last accessed:* 22/03/201515, BBC online.

[27] Edmund Penning-Rowsell and Theresa Wilson. Gauging the impact of natural hazards: the pattern and cost of emergency response during flood events. *Transactions of the Institute of British Geographers*, 31(2):99–115, 2006.

[28] Natural England. Reducing coastal flood risk and adapting to climate change in Lancashire, July 2014, Press release, Available at: https://www.gov.uk/government/news/reducing-coastal-flood-risk-and-adapting-to-climate-change-in-lancashire, *Last accessed:* 23/05/2015.

[29] Defra. Reducing the risks of flooding and coastal erosion. An investment plan, 2014, Available at: https://www.gov.uk/government/publications/reducing-the-risks-of-flooding-and-coastal-erosion-an-investment-plan-2014, *Last accessed:* 16/04/2015, Defra.

[30] Stewart Milne Group. Company website, 2015, Available at: http://www.stewartmilne.com/, *Last accessed:* 27/03/2015.

[31] Persimmon Plc. Company website, 2015, Available at: http://corporate.persimmonhomes.com/about-us/our-brands/space-4, *Last accessed:* 16/04-2015.

[32] Cabinet Office. Government Construction Strategy, 2011, Report, Available at: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/61152/Government-Construction-Strategy_0.pdf, *Last accessed:* 10/11/2014, Cabinet Office.

[33] Julia Kollewe. Prefabs sprout as Britain embraces timber-frame housing, 2012, Available at: http://www.theguardian.com/business/2012/nov/12/prefabs-britain-timber-frame-persimmon, *Last accessed:* 16/04/2015, Guardian Online.

[34] United Kingdom Forestry Commission. UK Timber market statement - December 2013. Technical report, United Kingdom Forestry Commission, 2013.

[35] Jack Porteous and Abdy Kermani. *Structural timber design to Eurocode 5.* John Wiley & Sons, second edition, 2013.

[36] US Census Bureau. Characteristics of New Housing - Highlights of 2013, 2013, Raw data set, Online dataset available at: `http://www.census.gov/construction/chars/microdata.html`, *Last accessed:* 27/03/2015, *Survey of Construction microdata for US housing market.*

[37] R B Wainwright. *Timber frame construction.* Timber Research and Development Association, High Wycombe, 1988.

[38] Helmut G L Prion and Frank Lam. Shear walls and diaphragms. In S Thelandersson and H J Larsen, editors, *Timber Engineering*, chapter 20, pages 383 – 408. John Wiley & Sons, 2003. ISBN 9780470844694.

[39] Institution of Structural Engineers and Trada. *Manual for the design of timber building structures to Eurocode 5.* London : Institution of Structural Engineers, London, 2007.

[40] Marcia Patton-Mallory, Richard M Gutkowski, and Lawrence A Soltis. Racking performance of light-frame walls sheathed on two sides. Technical report, Forest Products Laboratory, 1984.

[41] BSI. PD 6693-1:2012 Recommendations for the design of timber structures to Eurocode 5: Design of timber structures General. Common rules and rules for buildings, 2012, British Standards Institute.

[42] Alexander Salenikovich and Mario Payeur. Infuence of vertical loads on lateral resistance of light-frame shear walls. In *Proceedings of the World Conference on Timber Engineering*, Trentino, Italy, 2010.

[43] JD Dolan and B Madsen. Monotonic and cyclic nail connection tests. *Canadian Journal of Civil Engineering*, 19(1):97–104, 1992.

[44] Minoru Okabe, Naohito Kawai, and Seiji Takada. Experimental analysis for estimating strength and stiffness of shear walls in wood framed con-

struction. In *Proceedings of the World Conference on Timber Engineering*, Whistler, Canada, 2000.

[45] Bo Källsner, Ulf Arne Girhammar, and Liping Wu. A simplified plastic model for design of partially anchored wood-framed shear walls (34-15-1). In *Proceedings of CIB-W18*, Venice, Italy, 2001.

[46] Bo Källsner and Ulf Arne Girhammar. Influence of framing joints on plastic capacity of partially anchored wood frame shear walls (37-15-3). In *Proceedings CIB-W18 Meeting*, Edinburgh, Scotland, 2004.

[47] Ulf Arne Girhammar and Bo Källsner. Tests on partially anchored wood-framed shear walls. In *Proceedings of the World Conference on Timber Engineering*, Lahti, Finland, 2004.

[48] Bo Källsner and Ulf Arne Girhammar. Plastic design of partially anchored wood-framed wall diaphragms with and without openings (38-15-5). In *Proceedingsof CIB-W18*, Karlsruhe, Germany, 2005.

[49] Roger L Tuomi and William J McCutcheon. Racking strength of light-frame nailed walls. *Journal of the Structural Division*, 104(7):1131–1140, 1978.

[50] Ulf Arne Girhammar, Bo Källsner, and Per-Anders Daerga. Recommendations for design of anchoring devices for bottom rails in partially anchored timber frame shear walls. In *Proceedings of the World Conference on Timber Engineering*, Trentino, Italy, 2010.

[51] Jack Porteous and Peter Ross. *Designers' guide to eurocode 5 design of timber buildings : En 1995-1-1*. London : ICE Publishing, London, 2013. ISBN 9780727741837.

[52] Jesus M. Menendez, Leitch Kenneth, and Robert Hairstans. Structural behavior of timber frame closed panels for specification in the united kingdom. In Kay-Uwe Schober, editor, *Cost Action FP1004: Experimental Research with Timber*, pages 155–160, Prague, 2014.

[53] BSI. BS EN 1995 Eurocode 5–Design of timber structures – Part 1-1: General rules and rules for buildings, 2003, British Standards Institute.

[54] Bernard George Neal. *The plastic methods of structural analysis 2^{nd} edition.* Chapman and Hall, 1977.

[55] Bo Källsner and Ulf Arne Girhammar. A plastic design procedure for wood frame wall diaphragms. In *Proceedings of the World Conference on Timber Engineering*, Miyazaki, Japan, 2008.

[56] J M Dinwoodie. *Timber : its nature and behaviour*. London : Spon, London, 2000.

[57] BSI. BS EN 13183-1:2005 Moisture content of a piece of sawn timber. Estimation by capacitance method, 2005, British Standards Institute.

[58] Samuel, V Glass and Samuel L Zelinka and others. Moisture relations and physical properties of wood. In Bergman, Richard and Cai, Z and Carll, CG and Clausen, CA and Dietenberger, MA and Falk, RH and Frihart, CR and Glass, SV and Hunt, CG and Ibach, RE and others, editor, *Wood handbook : wood as an engineering material*, chapter 4. Forest Products Laboratory, 2010.

[59] C Skaar. *Water in wood.* 1972.

[60] Les Joza and Luiz Carlos Oliviera. The structure of wood in relation to drying. *Western Dry Kiln Association*, (43rd meeting, Reno, Nevada), 1992.

[61] H J Blass, Step Programme, and Step/Eurofortech, editors. *Timber engineering : STEP.* Almere : Centrum Hout, Almere, 1995.

[62] Forest Products Laboratory (US). *Wood handbook: wood as an engineering material.* United States Government Printing, 1987.

[63] Douglas R Rammer and Steve G Winistorfer. Effect of moisture content on dowel-bearing strength. *Wood and fiber science*, 33(1):126–139, 2001.

[64] Joseph Denig, Eugene M Wengert, William Turner Simpson, et al. Drying hardwood lumber. 2000.

[65] B G Butterfield and B A Meylan. *Three-dimensional structure of wood : an ultrastructural approach.* London : Chapman and Hall, London, 1980.

[66] S Garvin, J Reid, and M Scott. Standards for the repair of buildings following flooding - C623, 2005, London: Construction Industry Research and Information Association.

[67] Alistair Bradley, Wen-Shao Chang, and Richard Harris. The effect of drying conditions on post flooding mechanical properties of timber shear walls. In *Proceedings of the World Conference on Timber Engineering*, Quebec, Canada, 2014.

[68] BSI. Publicaly Available Specification 64. Mitigation and recovery of water damaged buildings. Code of practice, 2013, British Standards Institute.

[69] Charles Peterson. Hand Held Moisture Meters, 2008, Available at: `http://woodflooringedu.org/archives/downloads/moisturemeters.pdf`, *Last accessed:* 25/03/2015.

[70] Philip Blakemore. The use of hand-held electrical moisture meters with commercially important Australian hardwoods. Part 1 – Executive summary, methods, results, conclusion & recommendations, 2003, Corporation, Forest & Wood Products Research & Development.

[71] N C Edwards. Procedure for the determination of species correction data for electrical resistance type moisture meters, 1974, Unpublished, CSIRO Div. For. Prod.

[72] Holger Forsén, Veikko Tarvainen, et al. *Accuracy and functionality of hand held wood moisture content meters.* Technical Research Centre of Finland Espoo,, Finland, 2000.

[73] B Kidd, A Tagg, M Escarameia, B von Christierson, J Lamond, and D Proverbs. Guidance and standards for drying flood damaged buildings. Signposting current guidance - BD2760, 2010, Department for Communities and Local Government.

[74] M C Phillipson, P H Baker, M Davies, Z Ye, A McNaughtan, G H Galbraith, and R C McLean. Moisture measurement in building materials: an overview of current methods and new approaches. *Building Services Engineering Research and Technology*, 28(4):303–316, 2007. doi: 10.1177/0143624407084184.

[75] P Kearey and M Brooks. *An introduction to geophysical exploration*. Oxford : Blackwell Scientific, Oxford, 1984.

[76] O Sass and H A Viles. How wet are these walls? Testing a novel technique for measuring moisture in ruined walls. *Journal of Cultural Heritage*, 7(4): 257–263, 2006. doi: http://dx.doi.org/10.1016/j.culher.2006.08.001.

[77] Sergey V Dvinskikh, Marielle Henriksson, Antonio Lorenzo Mendicino, Stefania Fortino, and Tomi Toratti. Nmr imaging study and multi-fickian numerical simulation of moisture transfer in norway spruce samples. *Engineering Structures*, 33(11):3079–3086, 2011. doi: 10.1016/j.engstruct.2011.04.011. `http://www.sciencedirect.com/science/article/pii/S0141029611001726`.

[78] C D Araujo, A L MacKay, J R T Hailey, K P Whittall, and H Le. Proton magnetic resonance techniques for characterization of water in wood: application to white spruce. *Wood Science and Technology*, 26(2): 101–113, 1992. doi: 10.1007/bf00194466. `http://dx.doi.org/10.1007/BF00194466`.

[79] Ian D. Hartley, Siqun Wang, and Yang Zhang. Water vapor sorption isotherm modeling of commercial oriented strand panel based on species groups and resin type. *Building and Environment*, 42(10):3655 – 3659, 2007. ISSN 0360-1323. doi: http://dx.doi.org/10.1016/j.buildenv.2006.10.002. `http://www.sciencedirect.com/science/article/pii/S0360132306002861`.

[80] Qinglin Wu and Otto Suchsland. Effect of moisture on the flexural properties of commercial oriented strandboards. *Wood and fiber science*, 29(1): 47–57, 1997.

[81] Qinglin Wu and Cheng Piao. Thickness swelling and its relationship to internal bond strength loss of commercial oriented strandboard. *Forest products journal*, 49(7/8):50–55, 1999.

[82] Yee Sze Ang. Strucutral performance of flooded timber buildings, 2012, MEng Dissertation - Unpublished, University of Bath.

[83] TRADA. Timber frame design for flood-prone sites, 2011, Wood Information Sheet (WIS) 2/3-64.

[84] FEMA. Flood Damage-Resistant Materials - Requirements for Buildings Located in Special Flood Hazard Areas, 2008, Technical bulletin, Department of Homeland Security.

[85] BRE. Repairing flood damage: foundations and walls, 1997, Building Research Establishment, Good Repair Guide 11 - Part 3, Buildings Research Establishment ltd.

[86] Robert E Dales, Harry Zwanenburg, Richard Burnett, and Claire A Franklin. Respiratory health effects of home dampness and molds among Canadian children. *American journal of epidemiology*, 134(2):196–203, 1991.

[87] Kristin J Cummings, Jean Cox-Ganser, Margaret A Riggs, Nicole Edwards, Gerald R Hobbs, and Kathleen Kreiss. Health effects of exposure to water-damaged new orleans homes six months after hurricanes katrina and rita. *American journal of public health*, 98(5):869, 2008.

[88] Elisabeth Heseltine and Jerome Rosen. *WHO guidelines for indoor air quality: dampness and mould*. WHO Regional Office Europe, 2009.

[89] Jonathon Taylor, Ka man Lai, Mike Davies, David Clifton, Ian Ridley, and Phillip Biddulph. Flood management: prediction of microbial contamination in large-scale floods in urban environments. *Environment international*, 37(5):1019–1029, 2011.

[90] Bs En. 300: 2006 oriented strand boards (osb). *Definitions, classification and specifications.*

[91] Jessica Lamond, David Proverbs, M Escarameia, and A Tagg. Towards improved guidelines for drying flood-damaged buildings. *Journal of Flood Risk Management*, 2013.

[92] M Escarameia, A Karanxha, and A Tagg. Quantifying the flood resilience properties of walls in typical uk dwellings. *Building Services Engineering Research and Technology*, 28(3):249–263, 2007.

[93] BRE. Drying out Buildings. BRE Digest 163, 1974, Buildings Research Establishment.

[94] BRE. Repairing flood damage: immediate action, 1997, Building Research Establishment, Good Repair Guide 11 - Part 1, Buildings Research Establishment ltd.

[95] Environment Agency. After a flood: Practical advice on recovering from flood, 2007, EA, Environment Agency.

[96] Jonathon Taylor, Phillip Biddulph, Michael Davies, Ian Ridley, Anna Mavrogianni, Eleni Oikonomou, and Ka man Lai. Using building simulation to model the drying of flooded building archetypes. *Journal of Building Performance Simulation*, 6(2):119–140, 2013.

[97] Victor Samwinga. *Homeowner satisfaction and service quality in the repair of UK flood-damaged domestic property.* PhD thesis, University of Wolverhampton, Jan 2009.

[98] Carl E. Pace. *Flood Proofing Tests: Tests of Materials and Systems for Flood Proofing Structures.* National Technical Information Service, 1988.

[99] H. Aglan. Field testing of energy-efficient flood-damage-resistant residential envelope systems summary report. Technical report, ORNL, 2005.

[100] R. J. Leichti, R. Staehle, and D. V. Rosowsky. A performance assessment of flood-damaged shearwalls. In *9th International Conference on Durability of Materials and Components*, Brisbane, Australia, 2002.

[101] Paul Lambert. Laboratory evaluation of the Dryair drying and heating system for "moisture flushing" of strucutral elements. Technical report, Centre for Infrastructure Management, Sheffield Hallam University, Sheffield, 2006.

[102] Clearblue Flood Drying. Company website, 2015, Available at: `http://www.clearbluefloodrying.com/`, *Last accessed:* 27/03/2015.

[103] May Cassar and Chris Hawkings, editors. *Engineering Historic Futures Stakeholders - Dissemination and Scientific Research Report.* 2007.

[104] Andy Tagg, Manuela Escarameia, and Jon Molinero Ortiz. Improving the

Flood Resilience of Buildings Through Improved Materials, Methods and Details: Report WP6. Technical report, 2007.

[105] Alistair Bradley. Visit to the Oxfordshire Stewart Milne factory, July 2012, Personal communication.

[106] National Building Agency. *Manual of timber frame housing: a simplified method*. Lancaster : Construction Press, Lancaster, 1980.

[107] N Belavendram. *Quality by design : Taguchi techniques for industrial experimentation*. London : Prentice Hall, London, 1995.

[108] Genichi Taguchi. *Introduction to quality engineering : designing quality into products and processes*. Tokyo : Asian Productivity Organization, Tokyo, 1986. ISBN 9283310837.

[109] Genichi Taguchi. *Introduction to quality engineering: designing quality into products and processes*. 1986.

[110] J.L. Rosa, A. Robin, M.B. Silva, C.A. Baldan, and M.P. Peres. Electrodeposition of copper on titanium wires: Taguchi experimental design approach. *Journal of Materials Processing Technology*, 209(3):1181 – 1188, 2009. ISSN 0924-0136. doi: http://dx.doi.org/10.1016/j.jmatprotec.2008.03.021.

[111] E. Barrado, M. Vega, R. Pardo, P. Grande, and J.L. Del Valle. Optimisation of a purification method for metal-containing wastewater by use of a taguchi experimental design. *Water Research*, 30(10):2309 – 2314, 1996. ISSN 0043-1354. doi: http://dx.doi.org/10.1016/0043-1354(96)00119-4.

[112] BS EN. 384. structural timber. determination of characteristic values of mechanical properties and density. *The British Standards Institution*, 2010.

[113] Johan Vessby, Bertil Enquist, and Bo Källsner. Directional Dependency in an OSB Sheathing-To-Framing Mechanical Connection. In *Proceedings of the World Conference of Timber Engineers 2014*, page 9, Quebec, 2014.

[114] Alexander Julian Salenikovich. *The racking performance of light-frame shear walls*. PhD thesis, Virginia Polytechnic Institute and State University, 2000.

[115] Ulf Arne Girhammar, Nils Ivar Bovim, and Bo Källsner. Characteristics of sheathing-to-timber joints in wood shear walls. In *Poceedings 8th World Conference of Timber Engineering*, pages 165–170, Lahti, Finland, 2004.

[116] BSI. BS EN 12512: 2001 Timber Structures—test methods—Cyclic testing of joints made with mechanical fasteners, 2001, British Standards Insititute.

[117] Les Jozsa, Luiz Carlos Oliveira, Association Western Dry Kiln, and Meeting Western Dry Kiln Association. The structure of wood in relation to drying, 1992. `http://hdl.handle.net/1957/5297`, Corvallis, Or. : Western Dry Kiln Association.

[118] Jonathan David Shanks, Wen-Shao Chang, and Kohei Komatsu. Experimental study on mechanical performance of all-softwood pegged mortice and tenon connections. *Biosystems engineering*, 100(4):562–570, 2008.

[119] JD Shanks and P Walker. Experimental performance of mortice and tenon connections in green oak. *Structural Engineer*, 83(17):40–45, 2005.

[120] Andrew Thomson, Richard Harris, Martin Ansell, and Peter Walker. Experimental performance of non-metallic mechanically fastened timber connections. *The Structural Engineer*, 88(17):25–32, 2010.

[121] Ricardo O Foschi. Load-slip characteristics of nails. *J Wood Sci*, 7:69–74, 1974.

[122] BSI. BS EN 594:2011 Timber Structures - Test Methods - Racking strength and stiffness of timber frame wall pannels, 2011, British Standards Institute.

[123] AC Bradley, Wen-Shao Chang, and Richard Harris. The effect of simulated flooding on the structural performance of light frame timber shear walls–an experimental approach. *Engineering Structures*, 106:288–298, 2016.

[124] W Muñoz, M Mohammad, A Salenikovich, and P Quenneville. Need for a harmonized approach for calculations of ductility of timber assemblies. In *Proceedings of CIB/W18*, volume 41, 2008.

[125] E Karacabeyli and A Ceccotti. Nailed wood-frame shear walls for seismic loads: Test results and design considerations. In *Proceedings of the Structural Engineers World Congress*, 1998.

[126] M Yasumura and N Kawai. Evaluation of wood framed shear walls subjected to lateral load. In *Proceedings of the 30th CIB-W18 Meeting, Universität Karlsruhe, Karlsruhe, Germany, Paper*, pages 30–15, 1997.

[127] I Smith, A Asiz, M Snow, and YH Chui. Possible canadian/iso approach to deriving design values from test data. In *CIB-W18 Meeting in Florence*, 2006.

[128] Arijit Sinha and Rakesh Gupta. Strain Distribution in OSB and GWB in Wood-Frame Shear Walls. *Journal of Structural Engineering*, 135(6): 666–675, June 2009. ISSN 0733-9445.

Appendix A

The Taguchi Method

The Taguchi Method used in Chapter 4 is described in full here. The process of experimentation and analysis of results using the Taguchi method is perhaps best described by an example. In *Quality by Design* by Belavendram [107], the following example is given, based on Taguchi's original work [108]. It is presented here as an illustration of the application and strengths of the Taguchi Method. For further information please also see [107, 108] and [109].

The Ina Seito Tile Company

In the late 1950's the Ina Seito tile company of Japan was experiencing high variability in the tiles it produced. The company had invested in a new tunnel kiln to increase productivity however, the dimensions of tiles produced were highly variable, with more than half falling outside of the specification. Discarding half the tiles was an expensive option so another solution was sought. Analysis showed that tiles baked in the centre of the kiln experienced much lower temperatures than those at the edge. Since redesign of the kiln was expensive, an alternative approach was adopted. Seven *factors* or, input variables, were identified. These were; Lime content, Granularity, Agalmatolite percentage, Agalmatolite type, Charge quantity, Waste return and Feldspar content. Each of these factors had two *levels*, or values, that it could take. This arrangement of *factors* and *levels* is shown in Table A.1.

Table A.1: Factor levels for the experiment performed by Taguchi at Ina Seito Tile Company. Seven factors are investigated, each taking two levels. Factor level is indicated by the number following the letter; A2 indicates Factor A at Level 2.

Factor	Level 1	Level 2
A Lime content	A1 5%	A2 1%
B Granularity	B1 Coarse	B2 Fine
C Agalmatolite percentage	C1 43%	C2 53%
D Agalmatolite type	D1 Current mix	D2 Cheaper mix
E Charge quantity	E1 1300kg	E2 1200kg
F Waste return	F1 0%	F2 4%
G Feldspar content	G1 0%	G2 55%

Factor levels are then assigned to an *orthogonal array* in such a way as to ensure equal proportions of experiments and equal proportions of remaining factor levels. Correct assignment to an orthogonal array produces a set of experiments that allow a fair comparison of each factor level as shown in Table A.2.

Table A.2: An example orthogonal array for the Ina Seito experiment. Here the levels indicated in Table A.1 are assigned to experiments. By performing these eight experimental runs, enough data is generated to evaluate the influence of each factor.

Experiment	A	B	C	D	E	F	G
1	1	1	1	1	1	1	1
2	1	1	1	2	2	2	2
3	1	2	2	1	1	2	2
4	1	2	2	2	2	1	1
5	2	1	2	1	2	1	2
6	2	1	2	2	1	2	1
7	2	2	1	1	2	2	1
8	2	2	1	2	1	1	2

In Table A.2 the principles of equal allocation and equal remaining factors can be seen. Column A shows four "1's" and four "2's". The same is true for each of the columns B-G. The factor levels are equally proportioned across all experiments. All factors are represented at level one and two in equal amounts. While factor A is at level 1, half of factor B is at level 2 and half at level 1. The same is true for all other factors. This ensures the remaining factors are also equally proportioned. As the number of factors or levels increases, the orthogonal array becomes more complex to arrange. By performing each experiment in Table A.2 enough data is generated to assess the impact of every factor level without having to perform experiments for every single possible combination of factor levels.

The results of the experiments are presented in a similar fashion to Table A.2. An additional column containing the results for each experimental combination is added to the end of the table. Here the results indicate the number of tiles that fall outside of the specification as a percentage. The results are given in Table A.3. In this case it is clear that less tiles falling outside of the specification is the target of optimisation.

Table A.3: Example results for an orthogonal array for a parameter design. The results of each experiment are given as a percentage of tiles falling outside the desired parameters. The smaller this result, the better the process is optimised.

Experiment	A	B	C	D	E	F	G	Failure rate (%)
1	1	1	1	1	1	1	1	16
2	1	1	1	2	2	2	2	17
3	1	2	2	1	1	2	2	12
4	1	2	2	2	2	1	1	06
5	2	1	2	1	2	1	2	06
6	2	1	2	2	1	2	1	68
7	2	2	1	1	2	2	1	42
8	2	2	1	2	1	1	2	26

Assuming 100 runs of each experiment are performed, the overall total number of experiments is 800. The mean failure percentage across all experiments can be calculated by taking the mean of all results for all experiments.

$$\bar{y} = \frac{16 + 17 + 12 + 6 + 6 + 68 + 42 + 26}{800} = 24.125\% \tag{A.1}$$

The mean failure rate across all the different experimental factor combinations is approximately 24%. What makes the technique particularly powerful is the ability to analyse the influence of just one factor on the outcome. For example, the effect of changing the lime content (Factor A) from 5% (A1) to 1% (A2) can be studied in a similar fashion to the overall average as was done in Eqn. A.1.

By comparing the mean failure rate of all experiments at level A1 (Experiments 1-4, Table A.3) with those at level A2 (Experiments 5-8, Table A.3) the relative effect on average failure rate as a result of changing the lime content percentage can be compared.

$$\overline{A1} = \frac{16 + 17 + 12 + 6}{400} \times 100\% = 12.75 \tag{A.2}$$

$$\overline{A2} = \frac{6 + 68 + 42 + 26}{400} \times 100\% = 35.50 \tag{A.3}$$

These data indicate that the reduction of lime content from 5% (A1) to 1% (A2) results in an increase in the number of tiles that fall outside of the specification of 22.75%. The remaining factors can be compared in a similar fashion; identifying the experiments at the relevant factor level and averaging the appropriate results. This allows a table such as the one shown in Table A.4 to be produced, where the ranking indicates the significance of the factors. The higher the ranking, the

Table A.4: Example results with ranking according to the difference between factor levels. The greater the difference between levels, the higher the ranking and the more influential the factor on the process outcome.

	A	B	C	D	E	F	G
Level 1	12.75	26.75	25.25	1900	30.50	13.50	33.00
Level 2	35.50	21.50	23.00	29.25	17.17	34.75	15.25
Difference	22.75	5.25	2.25	10.25	12.75	21.25	17.75
Rank	1	6	7	5	4	2	3

more significant the effect a particular factor has on the outcome. These results can also be plotted on what is termed a response chart, an example of which is shown in Figure A-1. The response chart allows the differences between factor levels to be more easily visualised. The overall mean failure rate of 24% is also plotted to assist in comparing the factor effects. In this example, in order to optimise the system towards minimising the percentage of tiles that fall outside of specification, the factor levels that result in the lowest value per factor are picked. That is; A1, B2, C2, D1, E2, F1 and G2. In order of ranking these are; A1, F1, G2, E2, D1, B2 and C2. It is also possible for more than one output variable to be considered. If, for example, an additional parameter such as tile breakage were of interest it can be easily analysed. The values in the results

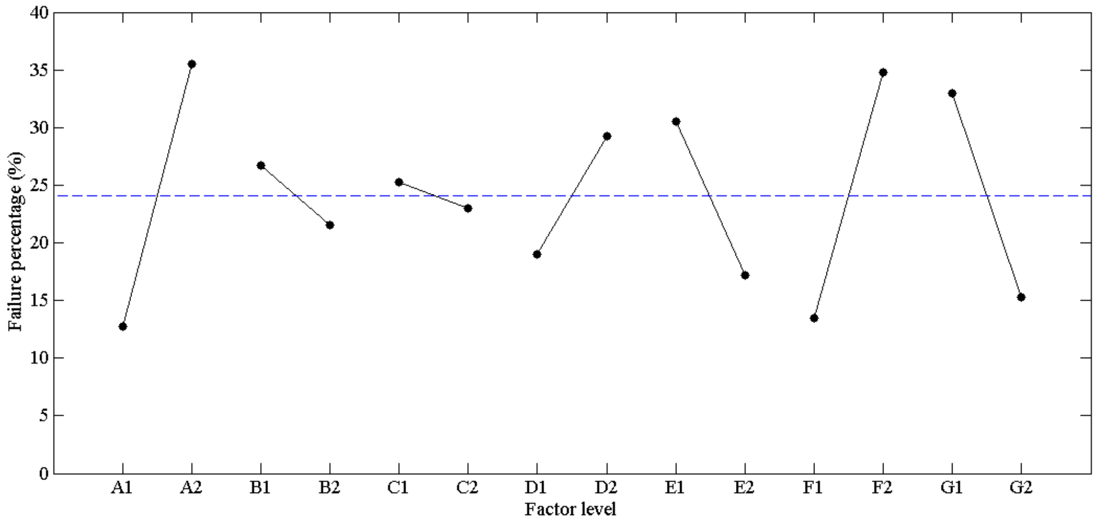


Figure A-1: The response chart for the example data. Results are plotted for each factor level. This plot is a visual representation of the data given in Table A.4 and allows the relative influence of factors to be easily visualised.

column in the previous example, Table A.3, are simply replaced with the relevant set of results and the data re-analysed. In this way multiple outputs can be considered so long as the appropriate data is collected during an experiment.

The results can be used to predict the process average at the optimum conditions. The predicted average, $\mu_{predicted}$ is given by Equation A.4.

$$\mu_{predicted} = \bar{y} + (\bar{A}1 - \bar{y}) + (\bar{F}1 - \bar{y}) + ... + (\bar{C}2 - \bar{y}) = -22\% \tag{A.4}$$

The failure percentage attributable to each factor at its optimum settings is subtracted from the overall mean. The sum of this calculation is then added to the overall mean to give the predicted outcome. This predicted failure value of -22% can be taken to be equivalent to 0%. Correct treatment of the negative predicted value is by the Omega transformation, details of which can be found in [107]. By use of the Omega transformation, the percentage failure is found to be approximately 0.4%. This is a significant reduction compared to the previous failure rate of more than 50%.

Figure A-1 also allows the relative influence of factors to be determined. Changing the level of factor B and C has little influence on the final result compared with changes to the other factor levels. In the specific example given here, Factor C represents the amount of Agalmatolite, reportedly the most expensive component in the mix. Although use of more Agalmatolite (Level C2) reduces the failure rate, its overall effect is small (just 2.25%). Given the cost of material in comparison to its effect on the output, selection of a less optimal factor level can be justified to reduce cost.

By choosing the optimum factors, the percentage of tiles that fall outside of specification is significantly reduced. Furthermore, the influence of each factor on the outcome can be observed, allowing informed judgements based on cost/benefit to be made. Thus the Taguchi method can be used not only to optimise a process but to do so using a judgement based approach built on the knowledge of the effect of each factor. Additional external information such as cost can be used in addition to the experimental data to make appropriate decisions regarding the process optimisation. In the previous example the Taguchi method was used to remedy the problem of manufactured tiles falling outside of specification without resorting to expensive machinery changes. Seven independent factors were studied simultaneously using only eight experimental set ups. Further more the method allows relative influence of factors to be studied and a system optimisation to be developed. In the set of experiments presented in this chapter, the Taguchi method is used to design the experimental setup and analyse the results. Its application allows the the relative importance of drying variables and optimum drying conditions to be determined.